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Title:	KiloPower Project - KRUSTY Experiment Nuclear Design
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KiloPower Project - KRUSTY Experiment Nuclear Design

NASA Glenn Research Center

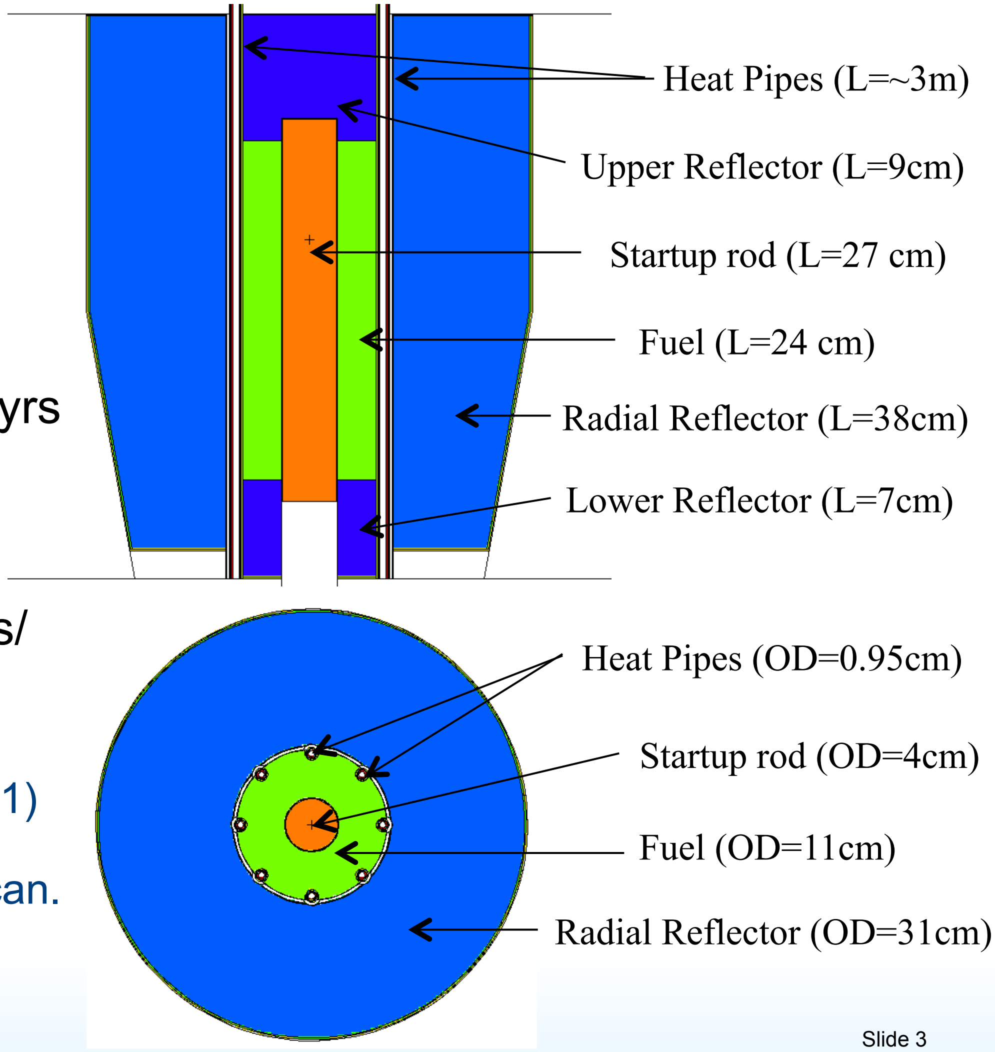
Topics Covered

- Reference Kilopower configuration
- Reference KRUSTY configuration
- KRUSTY Design sensitivities
- KRUSTY Reactivity Coefficients
- KRUSTY Criticality safety and control
- KRUSTY Core activation/dose
- KRUSTY Shielding, room activation/dose

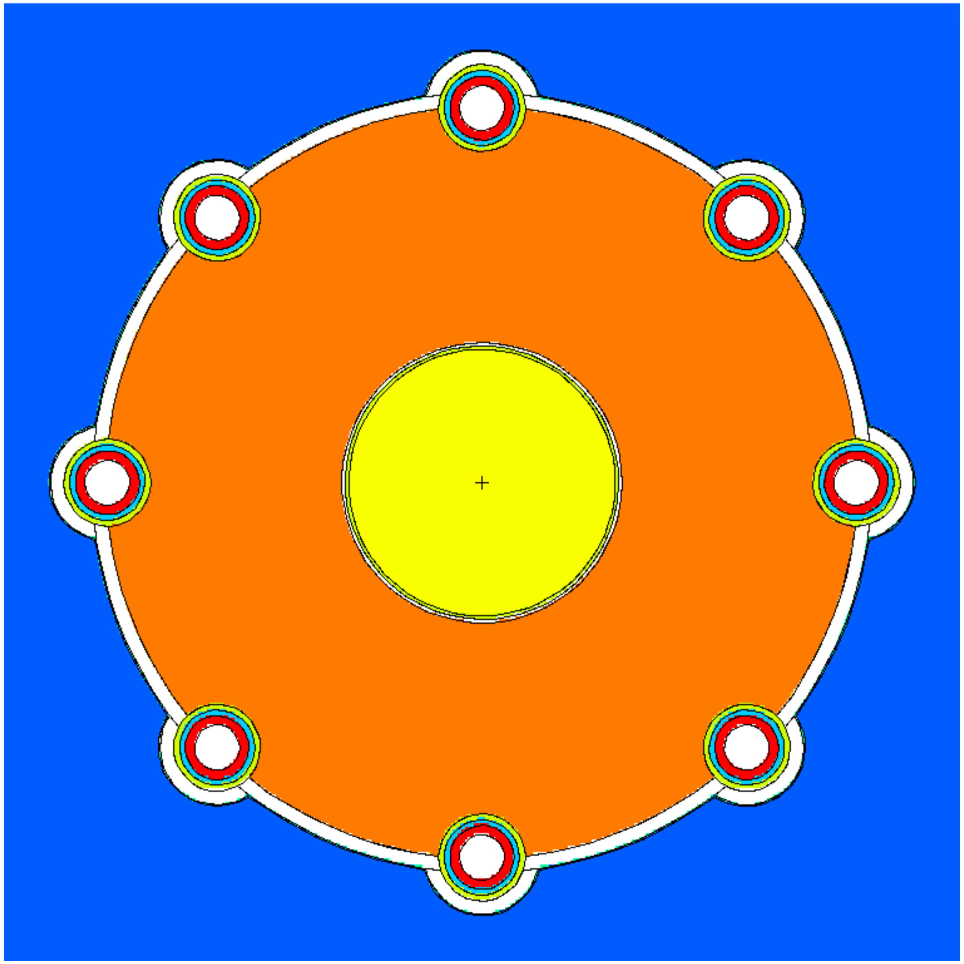
4.3-kWt Kilopower Reactor Concept

Reactor State	k-eff
Cold-BOL-Rod out	1.0321 +/- 0.0005
Cold-BOL-Rod in	0.9582+/- 0.0005
Warm-BOL-Rod out	1.0125+/- 0.0005
Warm-EOL-Rod out	1.0112 +/- 0.0005

- Peak fuel a/o burnup at 4.3 kWt, 15 yrs is 0.08% (essentially zero from a nuclear perspective).
- Biggest concern might be long-term fuel creep of fuel due to any stresses/ loads induced by expansion and support structure.
  - If we find this is a concern, we could 1) increase Mo fraction 2) decrease temperature, and/or 3) place fuel in can.



Thermal Performance at 4.3 kWt



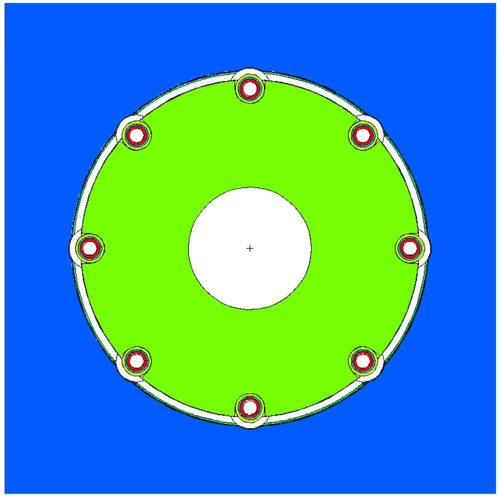
Component	**delta -T**
Proposed HP Na temp	1050 K
Fuel Conduction	~40 K
HP wall/internal	~13 K
Radiation gaps	>>100s K
He gas gaps	10s K
Sodium bond	~1 K
Forced contact gaps	????

With a failed heat pipe, the fuel dT goes to ~90 K and HP dT goes to ~22 K.

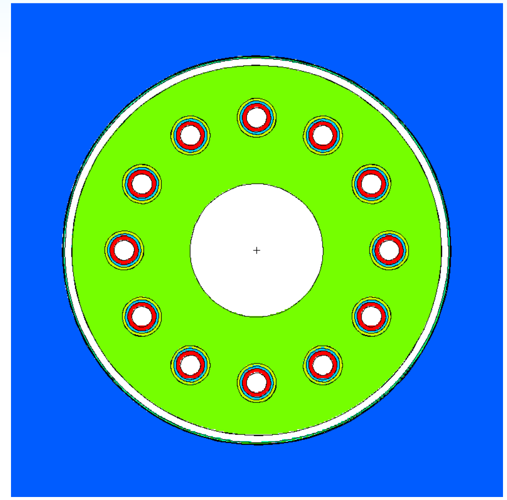
The conductance between HPs and fuel under pressurized contact in a vacuum was a big uncertainty. But results from recent experiments are looking pretty good.

FRINK model will eventually perform more detailed calculations, in steady-state and transients.

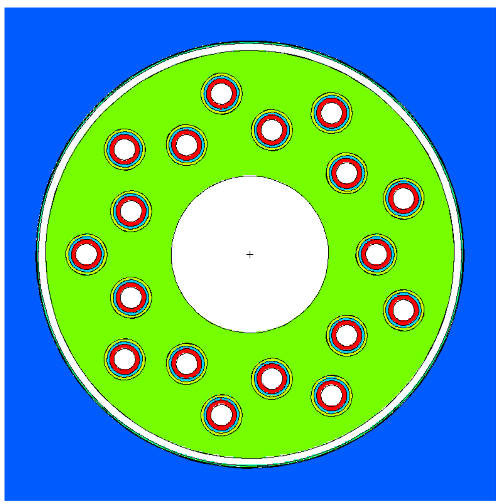
Cross sectional view of 4 cores (each 16x16 cm)



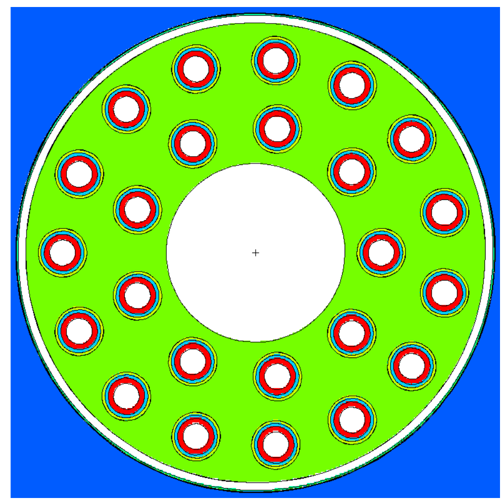
kpwr1a:
4.3 kWt
8 3/8” HPs



kpwr1b:
13.0 kWt
12 1/2” HPs



kpwr1c:
21.7 kWt
18 .525” HPs



kpwr1d:
43.3 kWt
24 5/8” HPs

Cores are configured so that failed HP peak fuel temp is similar to 4.3 kWt core
Nominal fuel temps are actually much lower in the higher power cores

Case Comparison

kpwr1a	kpwr2a	kpwr3a	kpwr4a	LANL case designator
4.3	13.0	21.7	43.3	Reactor Power (kWt)
15	15	15	15	Full-Power Years
8	12	18	24	Number of heat pipes (cm)
2.44	2.47	2.31	2.12	Fueled core L/D
11.0	12.0	13.2	15.0	Core OD (cm)
24.0	26.0	27.0	28.0	Fueled length (cm)
9.0	9.0	9.0	9.0	Top Axial Reflector length (cm)
7.0	7.0	7.0	7.0	Bot Axial Reflector length (cm)
0.952	1.270	1.334	1.587	Heat pipe OD (cm)
0.775	1.092	1.156	1.410	Heat pipe ID (cm)
10.0	10.0	10.0	10.0	Radref thickness (including can) (cm)
0.1	0.1	0.1	0.1	Radref outer wall thickness (cm)
1.9	2.2	2.5	2.9	Fuel volume (liters)

Overall Dimensions

kpwr1a	kpwr2a	kpwr3a	kpwr4a	LANL case designator
4.3	13.0	21.7	43.3	Reactor Power (kWt)
4.0	4.3	5.1	5.8	Safety Rod OD (cm)
11.0	12.0	13.2	15.0	Fuel OD (cm)
11.0	12.0	13.2	15.0	Can OD(cm)
11.5	12.6	13.8	15.6	Radref ID (cm)
31.5	32.6	33.8	35.6	Radref OD (cm)
				--Axial Dimensions
-19.0	-20.0	-20.5	-21.0	Bottom of core (cm)
-17.0	-18.0	-18.5	-19.0	Bottom of radref (cm)
-12.0	-13.0	-13.5	-14.0	Bottom of fuel (cm)
12.0	13.0	13.5	14.0	Top of fuel (cm)
21.0	22.0	22.5	23.0	Top of core (cm)
21.0	22.0	22.5	23.0	Top of radref (cm)
26.0	27.0	27.5	28.0	Bottom of shield (cm)
74.5	82.4	86.6	90.8	Top of shield (cm)

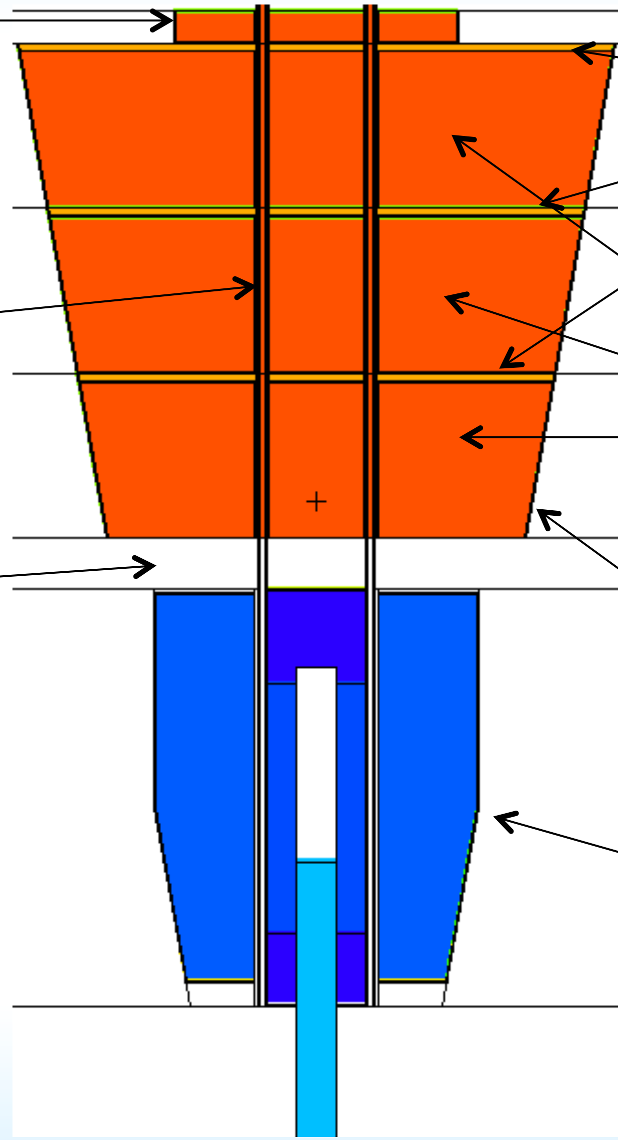
Nuclear Parameters

kpwr1a	kpwr2a	kpwr3a	kpwr4a	LANL case designator
4.3	13.0	21.7	43.3	Reactor Power (kWt)
0.09%	0.22%	0.32%	0.56%	Fuel Burnup (FIMA)
0.13%	0.33%	0.48%	0.84%	Fuel Swelling (Vol%)
2.3	6.0	8.7	15.1	Power density (W/cc)
28.4	32.9	37.9	43.7	Total U235 Inventory (kg)
0.0%	0.1%	0.2%	0.2%	Radref Be swelling
0.0005	0.0014	0.0020	0.0035	Burnup Reactivity Defect
0.0009	0.0023	0.0031	0.0055	Swelling Reactivity Defect
0.0014	0.0037	0.0051	0.0090	Total 15 year Reactivity Loss
0.0183	0.0167	0.0168	0.0167	Temp Defect (expansion and xs)
1.95E-05	2.20E-05	2.25E-05	2.30E-05	Average fuel RTC
4.9	11.2	15.1	26.0	dT (K/yr) w/o rod movement

Reactor Masses

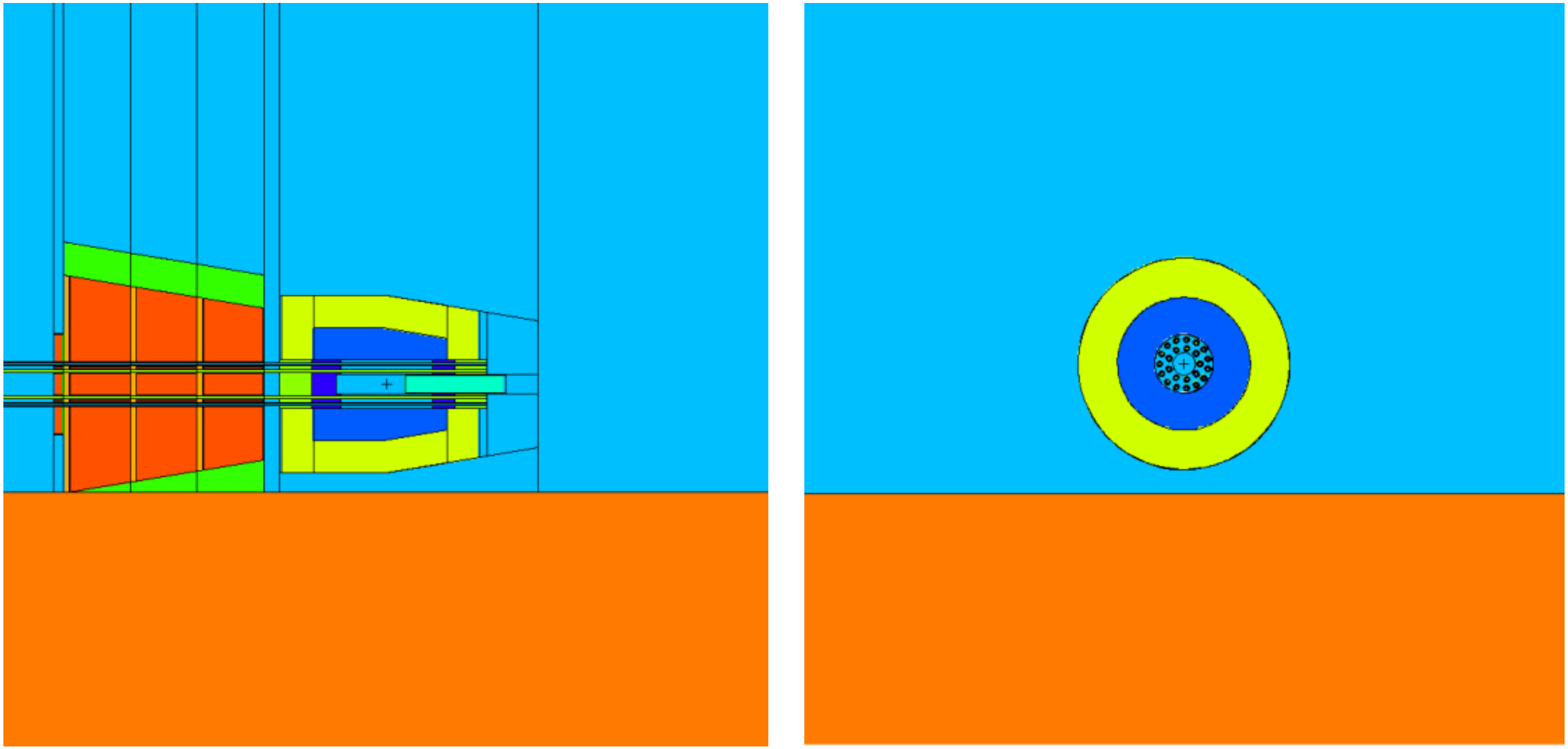
kpwr1a	kpwr2a	kpwr3a	kpwr4a	LANL case designator
4.3	13.0	21.7	43.3	Reactor Power (kWt)
				--Component Masses
32.9	38.1	43.8	50.5	Fuel
3.6	3.8	4.2	4.7	Axial Reflector
0.0	0.1	0.1	0.1	Fuel liner/can
4.1	10.4	18.2	34.8	Heat pipes (entire length)
0.3	1.1	2.0	4.3	Heat pipe coolant
72.5	80.0	86.7	95.6	Rad Ref Meat
4.5	4.9	5.3	5.7	Rad Ref Clad
4.1	5.2	7.4	9.9	Safety Rods + mechs
12.2	14.3	16.8	20.6	Rx structure (+ shield attach)
134.2	157.8	184.4	226.3	Total Reactor Mass

Kilopower Shield
(shown is kpwr1a = 4.3 kWt/15 yr)



kpwr1a = 62 kg LiH, 17 kg SS, 91 kg DU

Mars Surface Power Shielding



The option shown is to place system on its side and place shadow shield in direction of outpost. 4pi shielding (or at least 2pi) required to reduce sky shine to outpost. In this option the radial shielding is B4C.

Topics Covered

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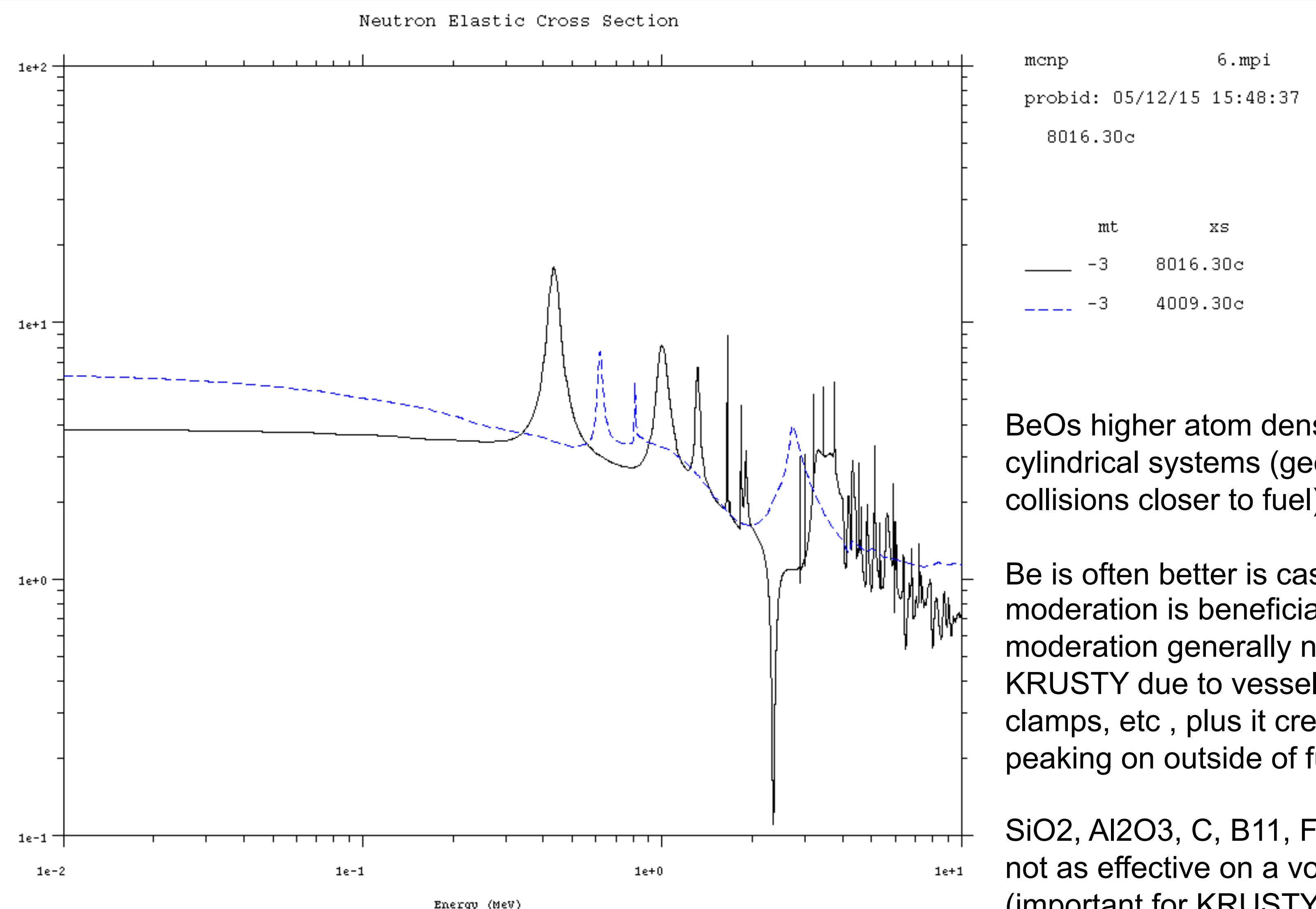
- **Reference KRUSTY configuration**
- KRUSTY Design sensitivities
- KRUSTY Reactivity Coefficients
- KRUSTY Criticality safety and control
- KRUSTY Core activation/dose
- KRUSTY Shielding, room activation/dose

Material Selection

- Fuel – U8Mo
  - The short story - straight U better neutronically, but 8Mo desired for thermal cycling capability.
- Neutron Reflector - BeO
  - BeO much better than Be,
    - BeO worth $4 to $5 more depending on vessel, MLI, etc
    - BeO has significantly lower RTC (temp feedback) than Be
    - BeO provides better shielding than Be
    - BeO allows more space for additional shielding
  - BeO is generally more expensive, but was considered worth the cost.
  - Based on discussions with vendors, the ability to fabricate BeO parts puts a reasonable limit at a diameter of 15"
    - This makes for a ~15 cm, 6" thick radial reflector.
  - 95% dense material was selected because it is much cheaper than 98%
    - Even though 98% would have made things slightly easier elsewhere.

Why BeO is best reflector



99% TD Be 1.83 g/cc: A=9 -- .122 a/bn-cm
95% TD BeO 2.85 g/cc: A=12.5 -- .137 a/bn-cm

BeOs higher atom density important for cylindrical systems (geometry prefers collisions closer to fuel).

Be is often better is cases where moderation is beneficial, but moderation generally not good for KRUSTY due to vessel, multifoil, clamps, etc , plus it creates power peaking on outside of fuel.

SiO2, Al2O3, C, B11, Fe, Ni, Cu, etc. not as effective on a volumetric basis (important for KRUSTY and criticality safety, and definitely not preferred from a mass basis for space application

Material Selection

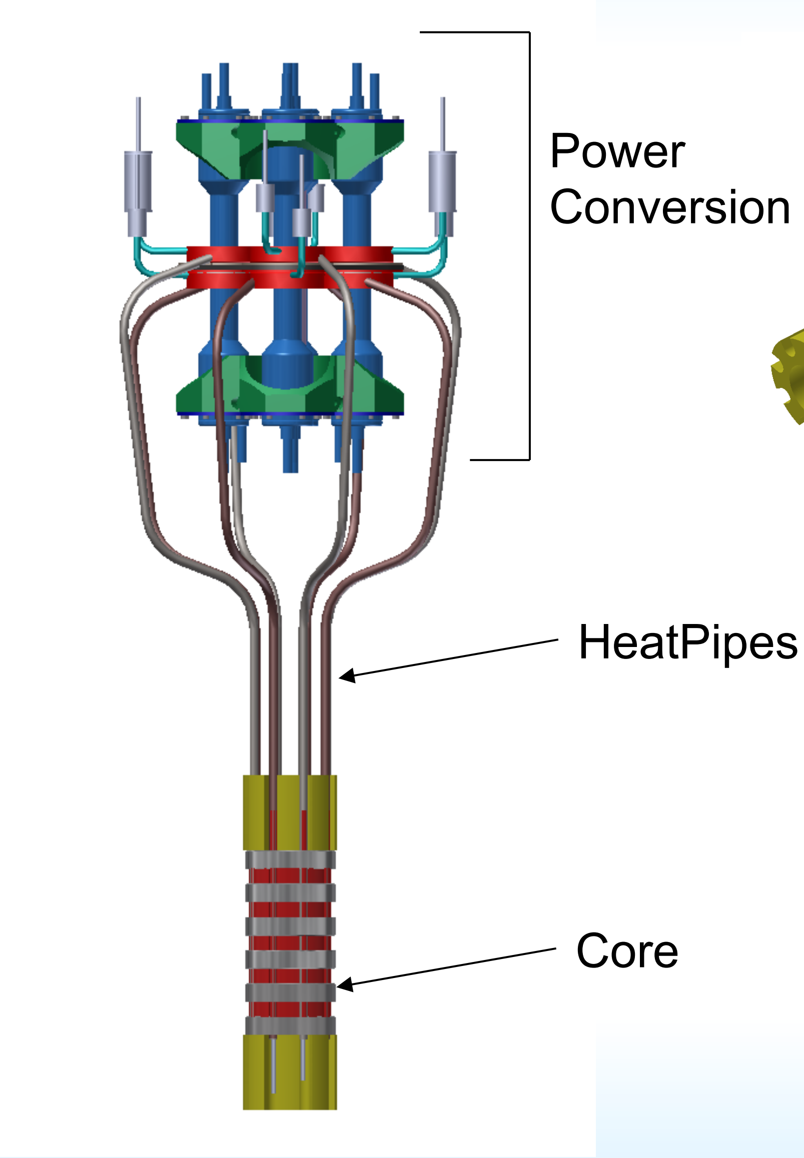
- Heat pipes
  - Haynes 230 wall
    - Higher temperature strength than SS316
  - Na working fluid
    - Generally Na better than K when T>1000 K
  - Haynes 230 wick (may be different)
- Moly material diffusion barrier between Haynes and UMo
  - Thin coating modeled
- SS316 clamp rings, vessel and inner radref sleeve
- B4C neutron shield and SS316 gamma shield
  - Radial shield all SS316
  - Axial shield layer of B4C sanwiched between SS316
    - Complicated selection, discussed later.

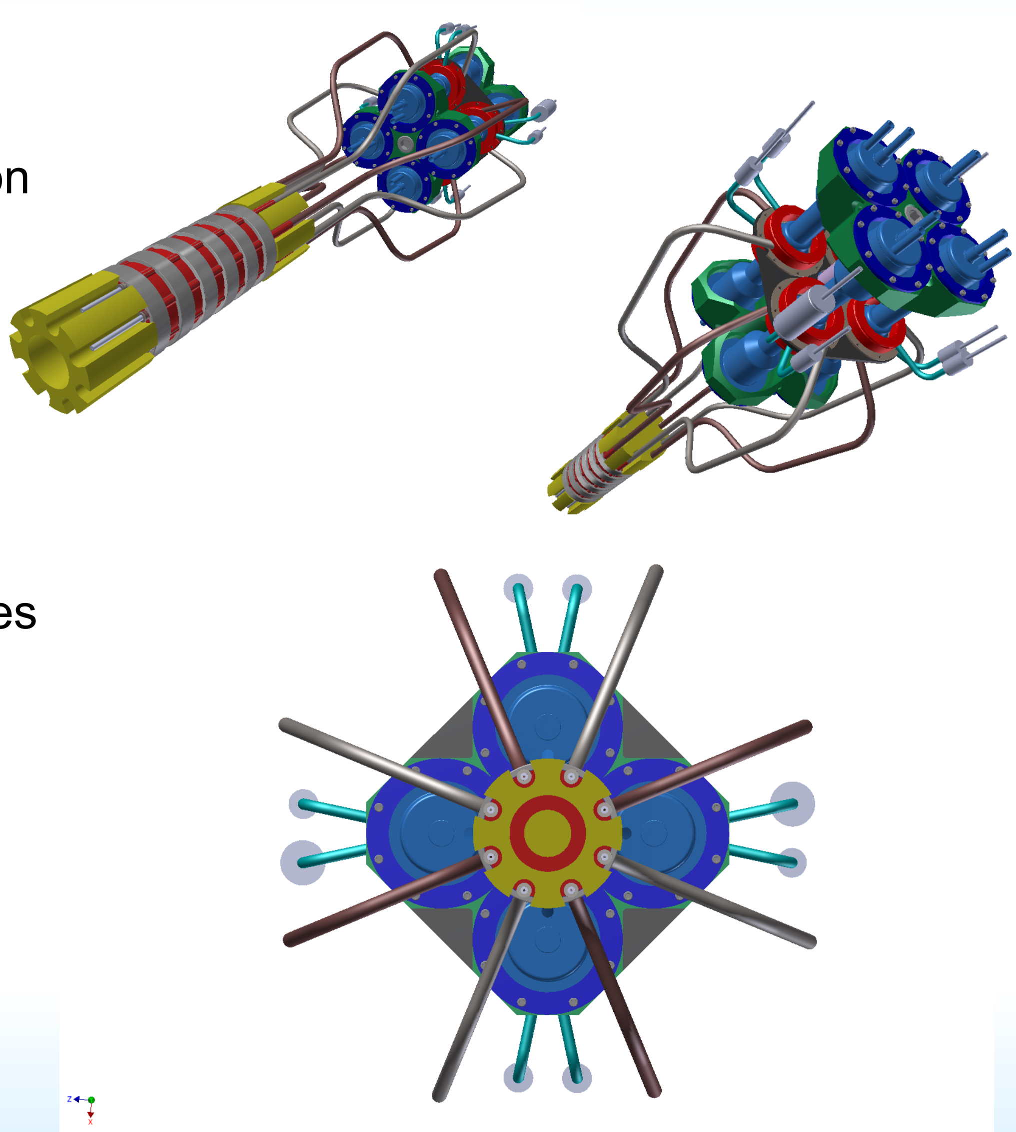
Design Process

- Shield and Reflector design process was an iterative process involving
  - MCNP model calculations
  - Mechanical design for operation and assembly
  - Materials availability and cost
  - Programmatic considerations

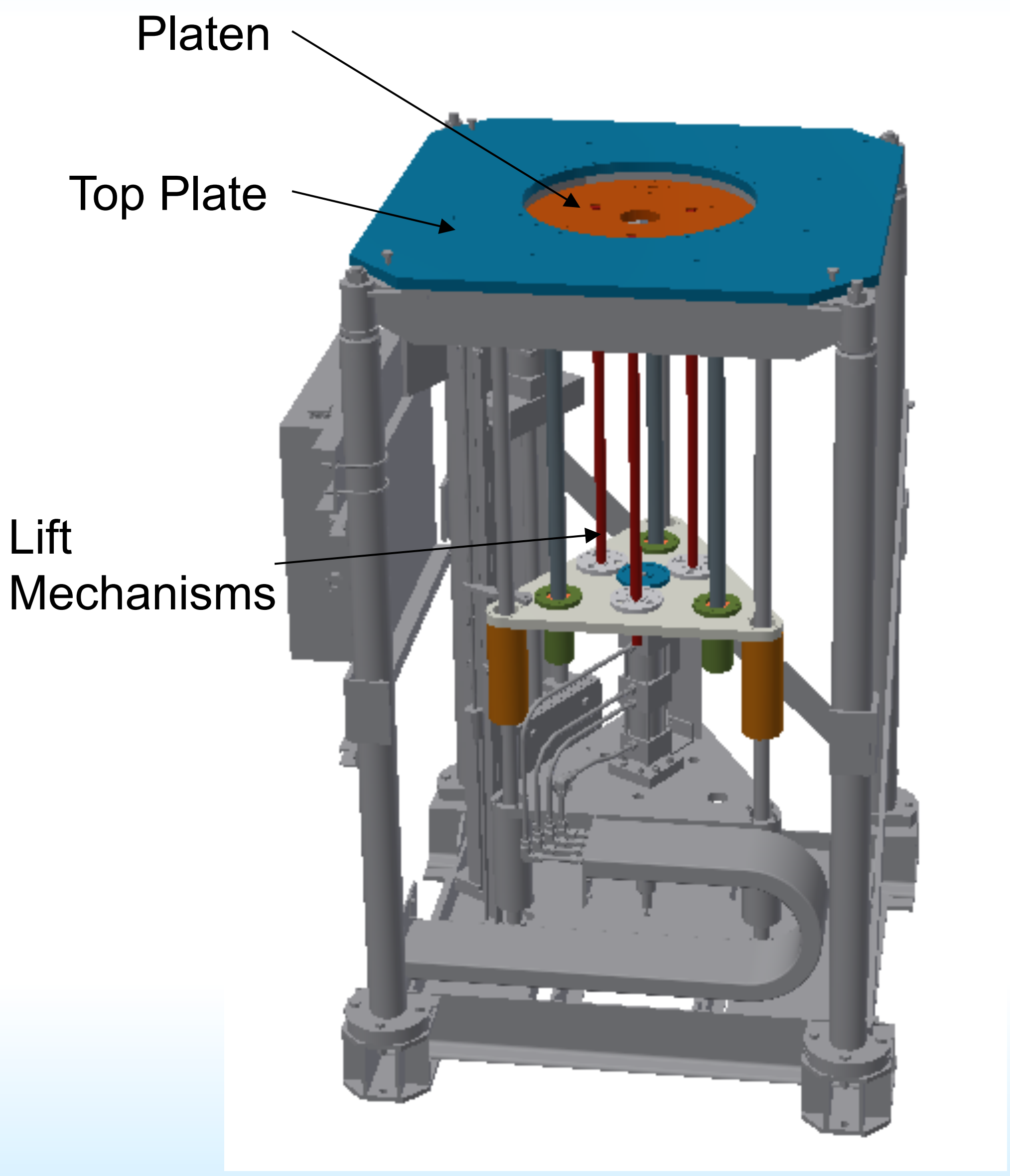
- There are many ways to solve this problem, solution presented represents a compromise of all the above in some form or another.

KRUSTY



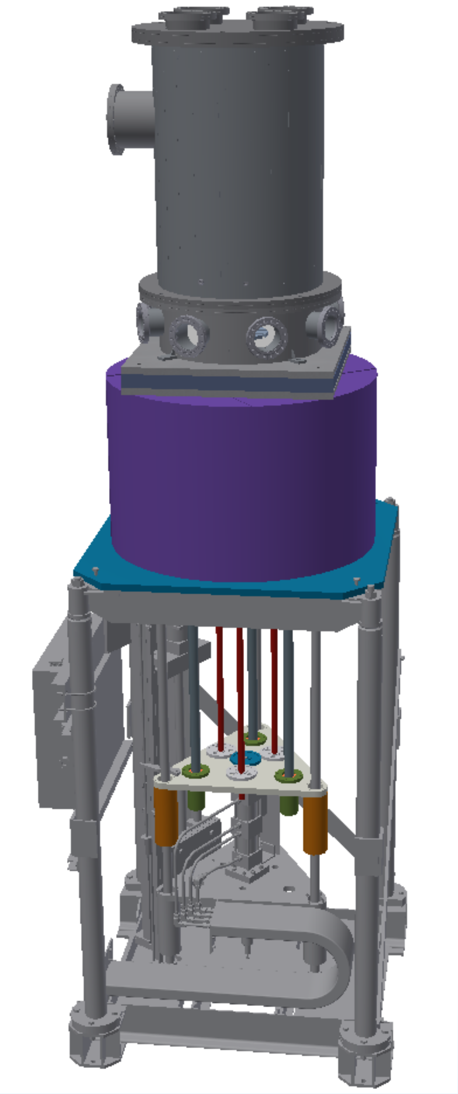


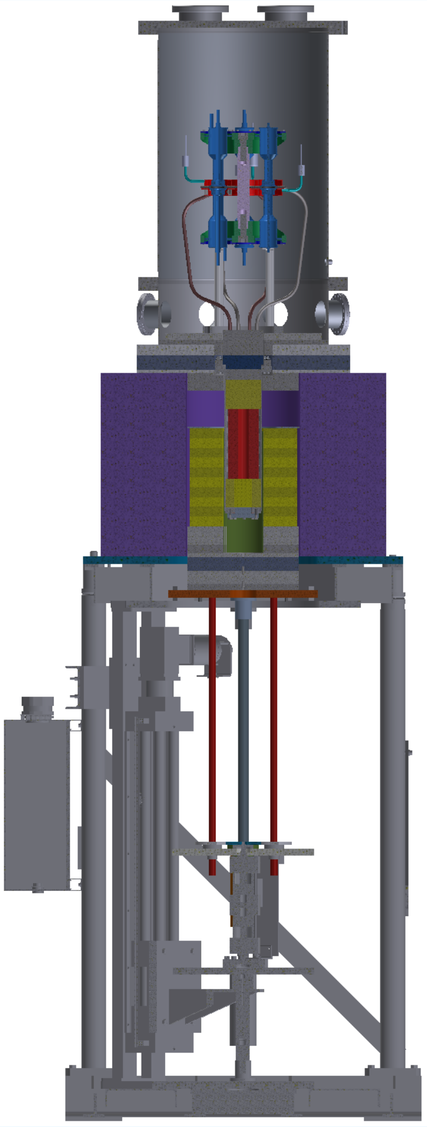
COMET



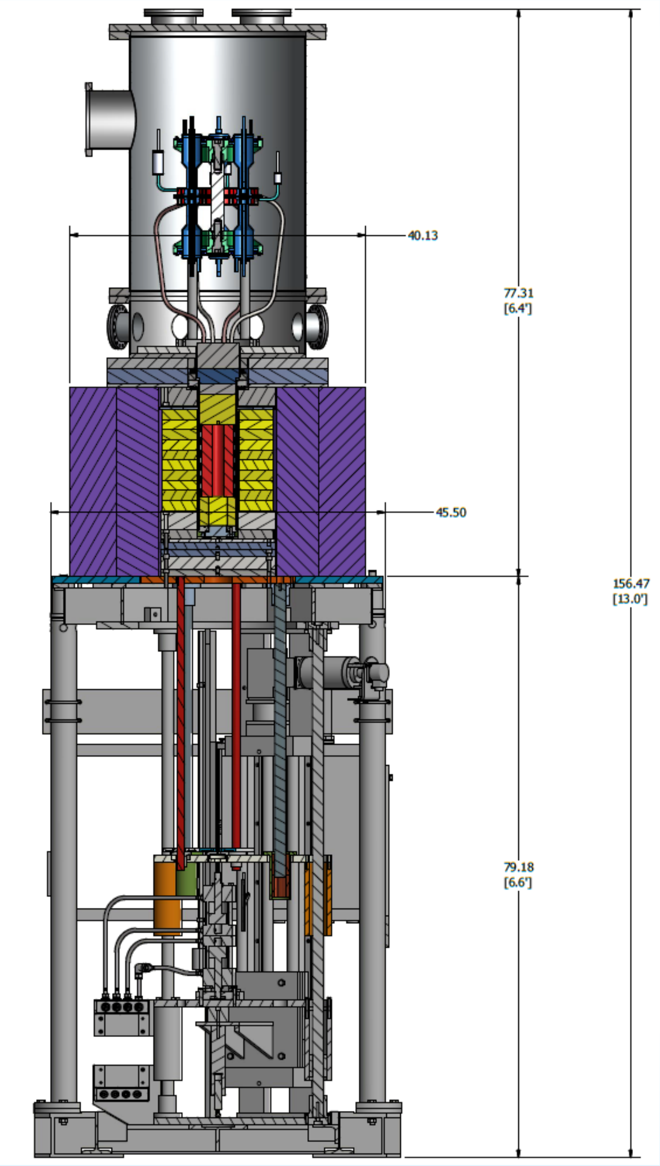
- COMET the test fixture being utilized at DAF.
- Platen raises and lowers by hydraulics and drive motors

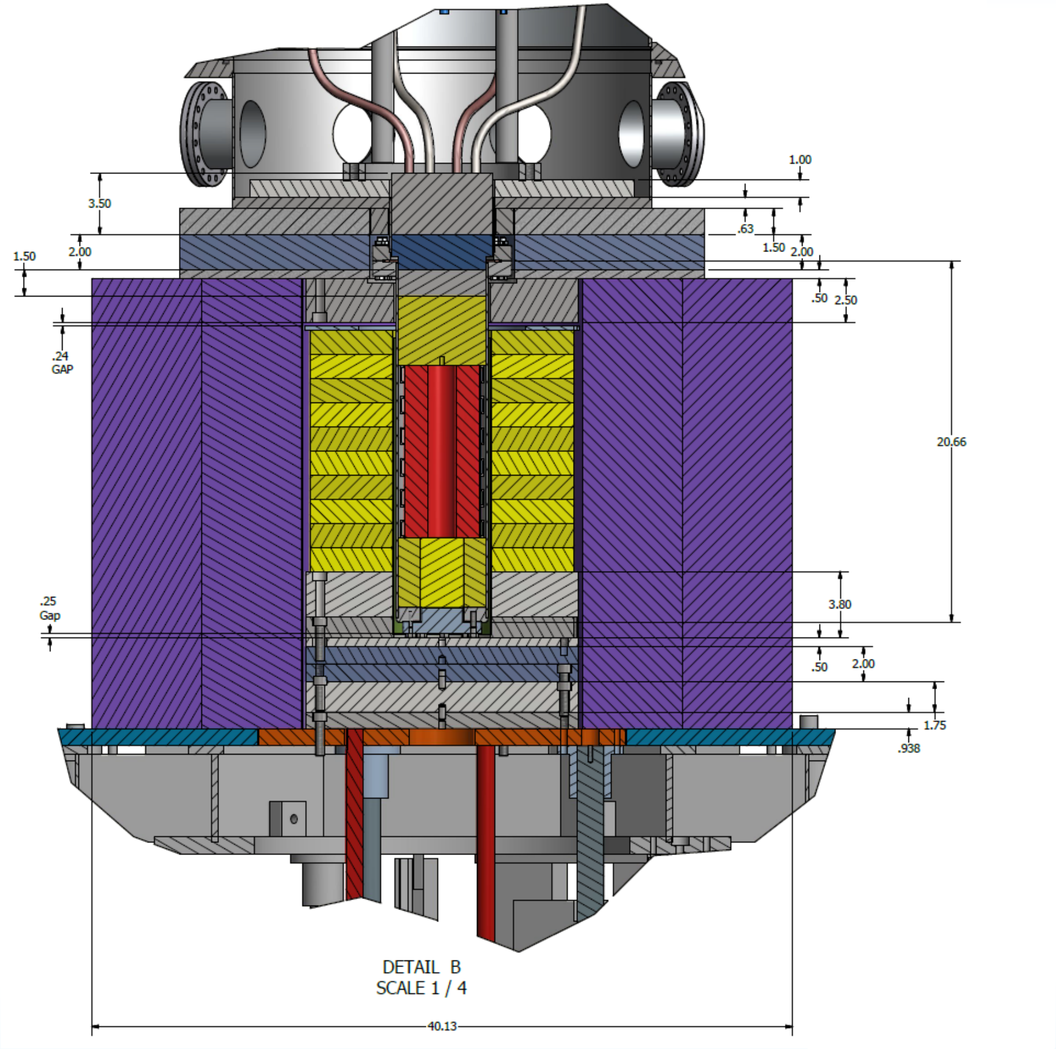
KRUSTY mounted on COMET



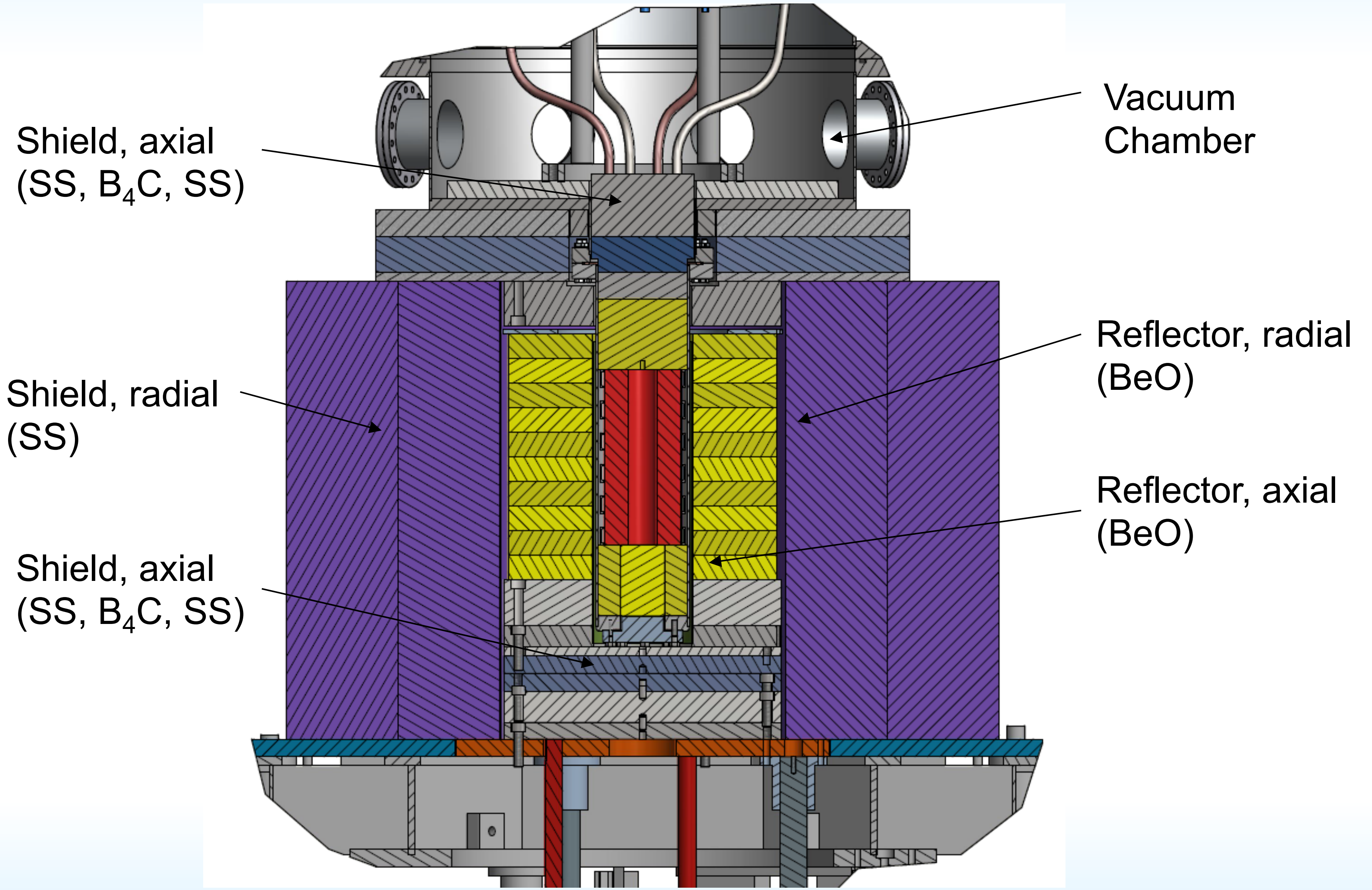


KRUSTY mounted on COMET

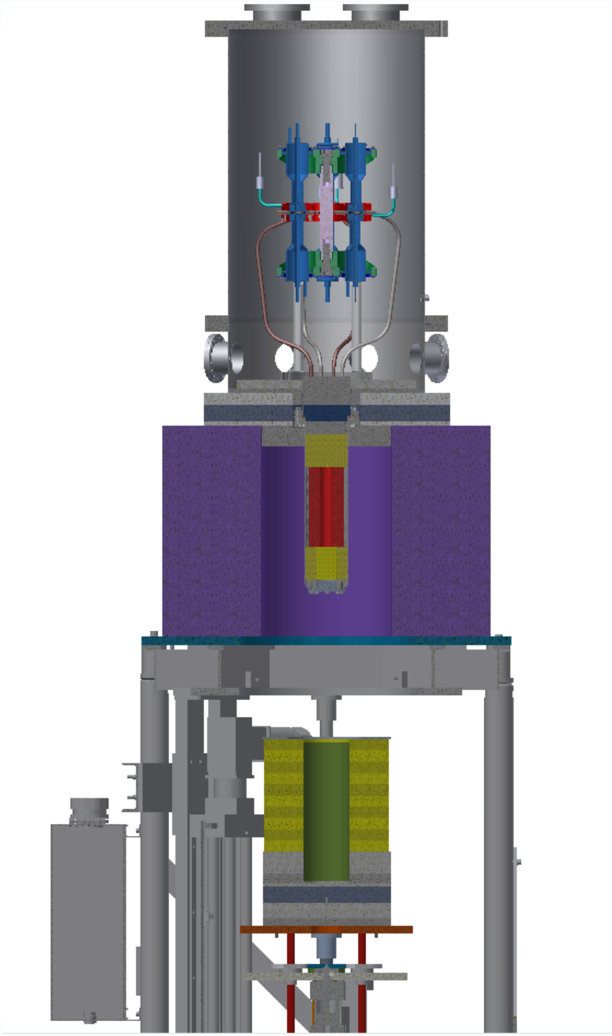




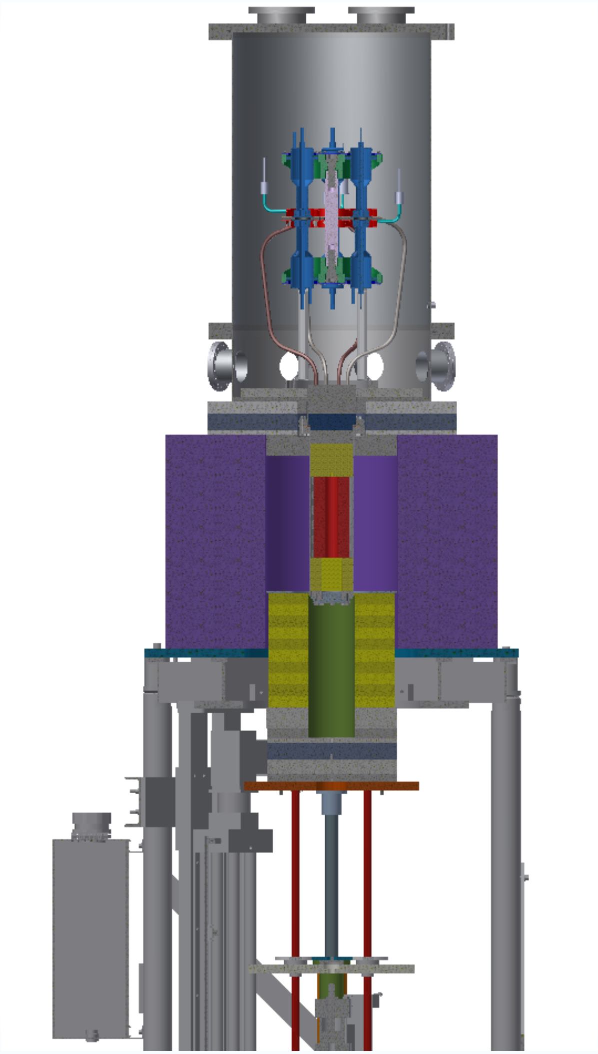
Reactor Configuration



Platen Positions

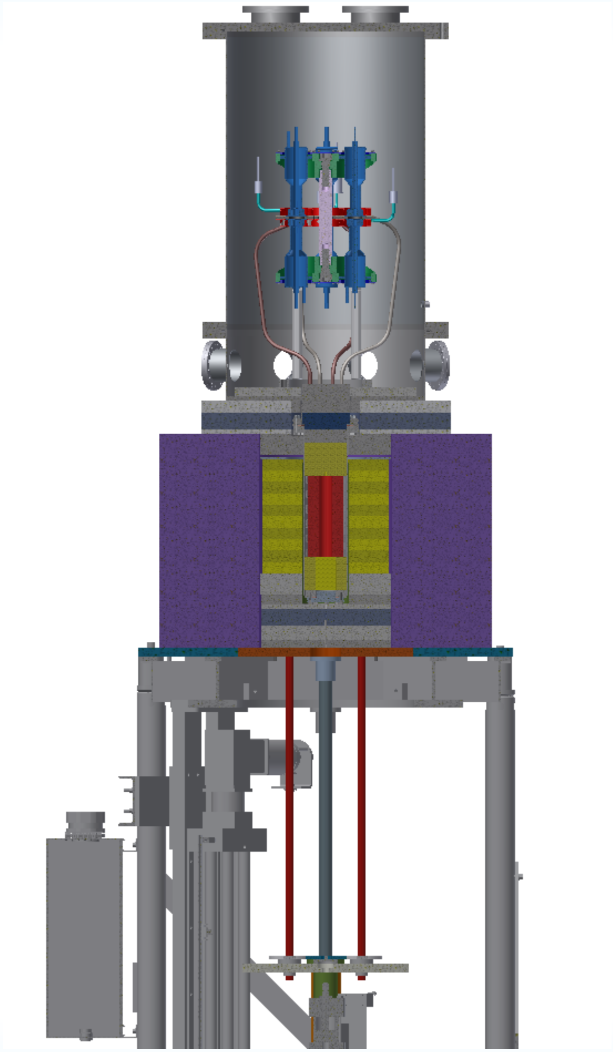


Load

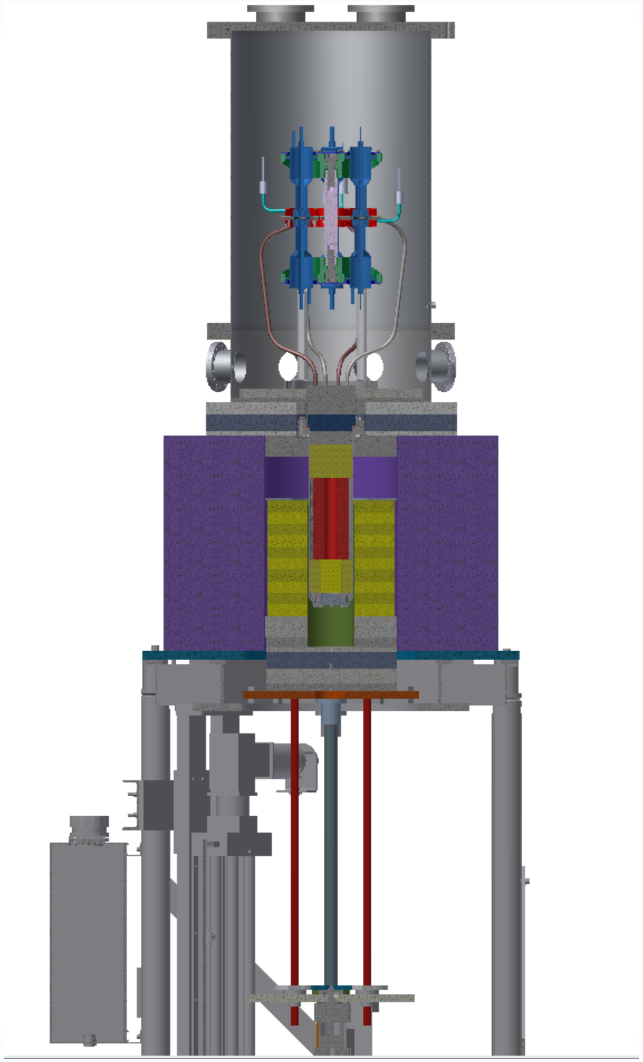


Approach to Critical

Platen Positions

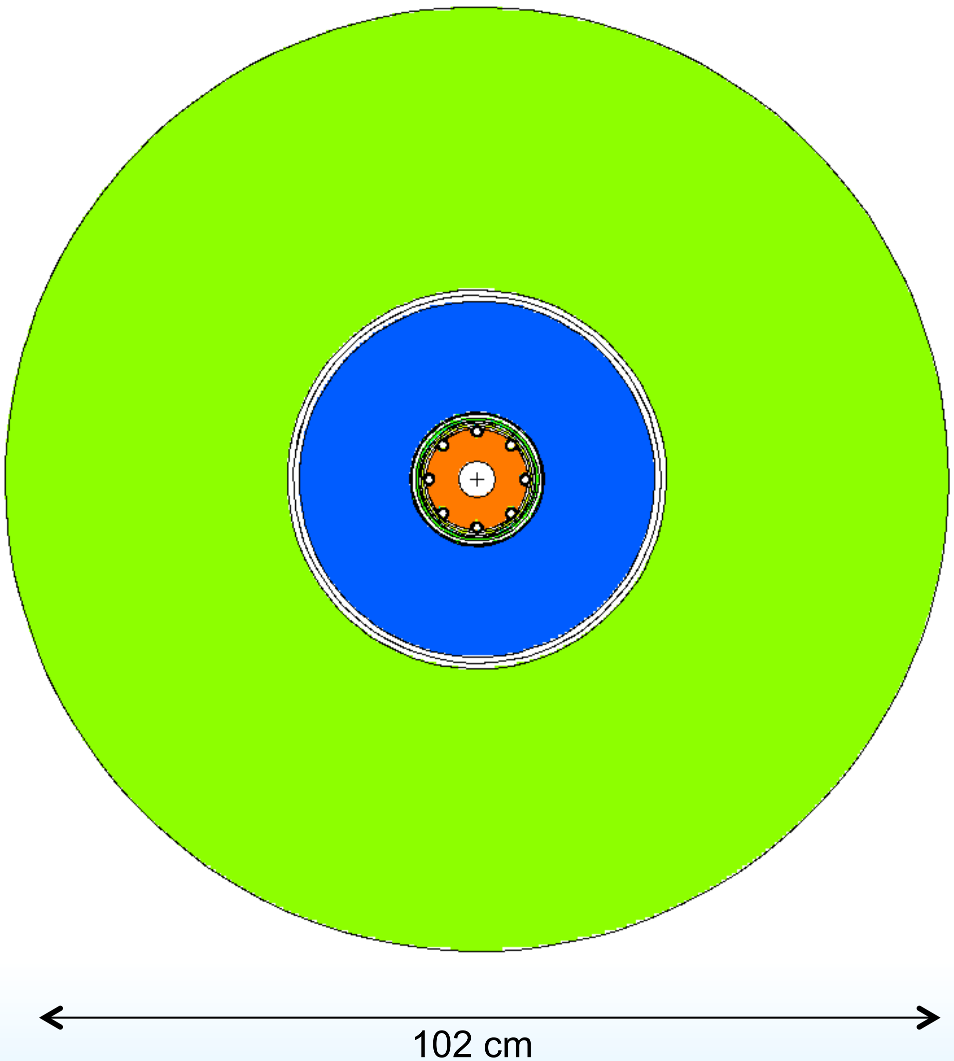


Operation



Scram

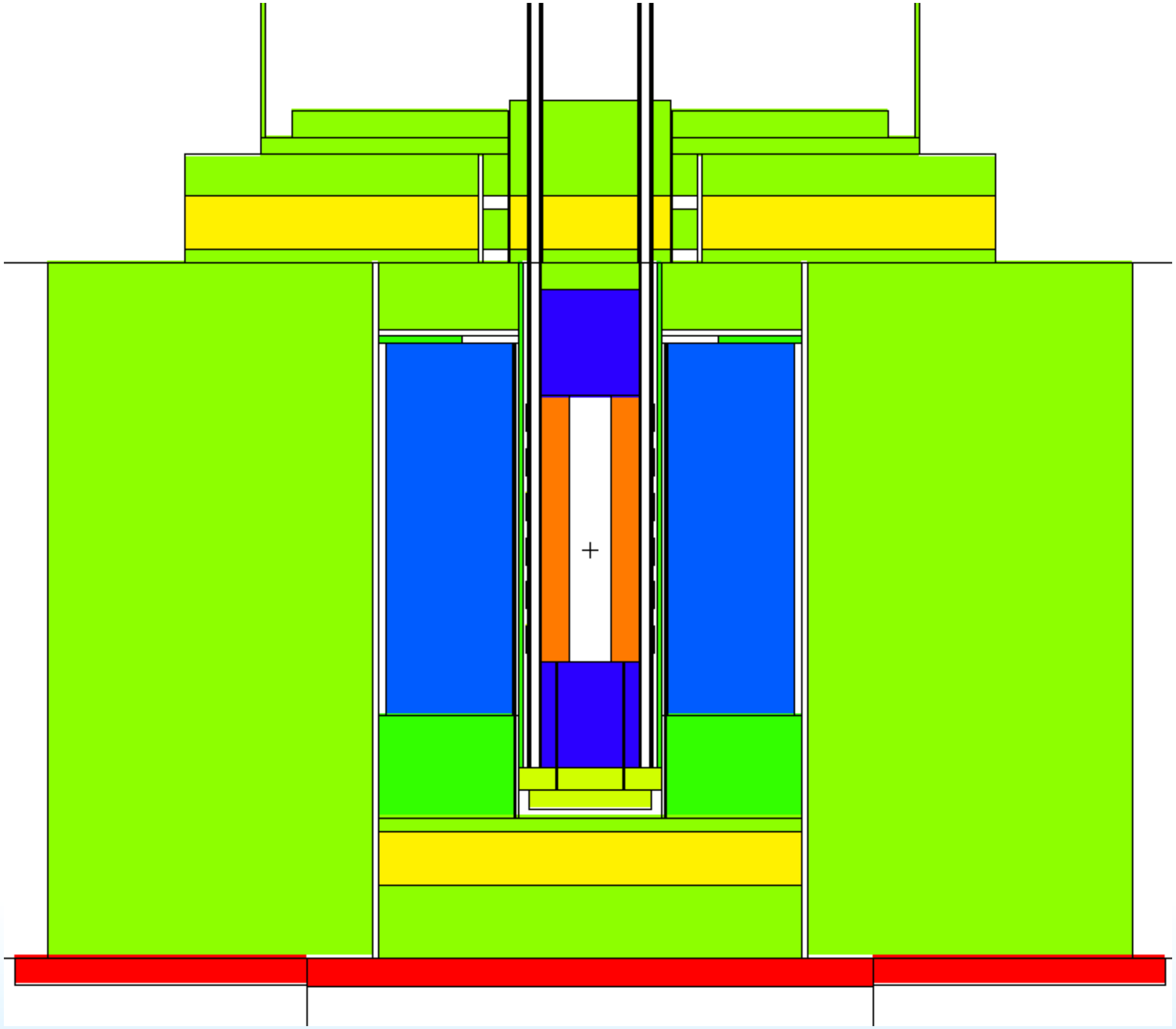
KRUSTY MCNP Model



krst1ag	LANL case designator
U8Mo	Fuel material
Mo	Fuel liner material
Hayn230	Heat pipe wall
Hayn230	Heat pipe wick
Hayn230	Clamp Rings (SS316?)
Na	Coolant
BeO	RadRef Material
BeO	AxRef material
SS316	Vacuum Can
SS316	Radref inner sleeve
B4C	Neutron Shield
SS316	Gamma Shield
4.3	Reactor Power (kWt)
0.0023	Full-Power Years
38.4	Radref OD (cm)
101.9	Shield OD (cm)

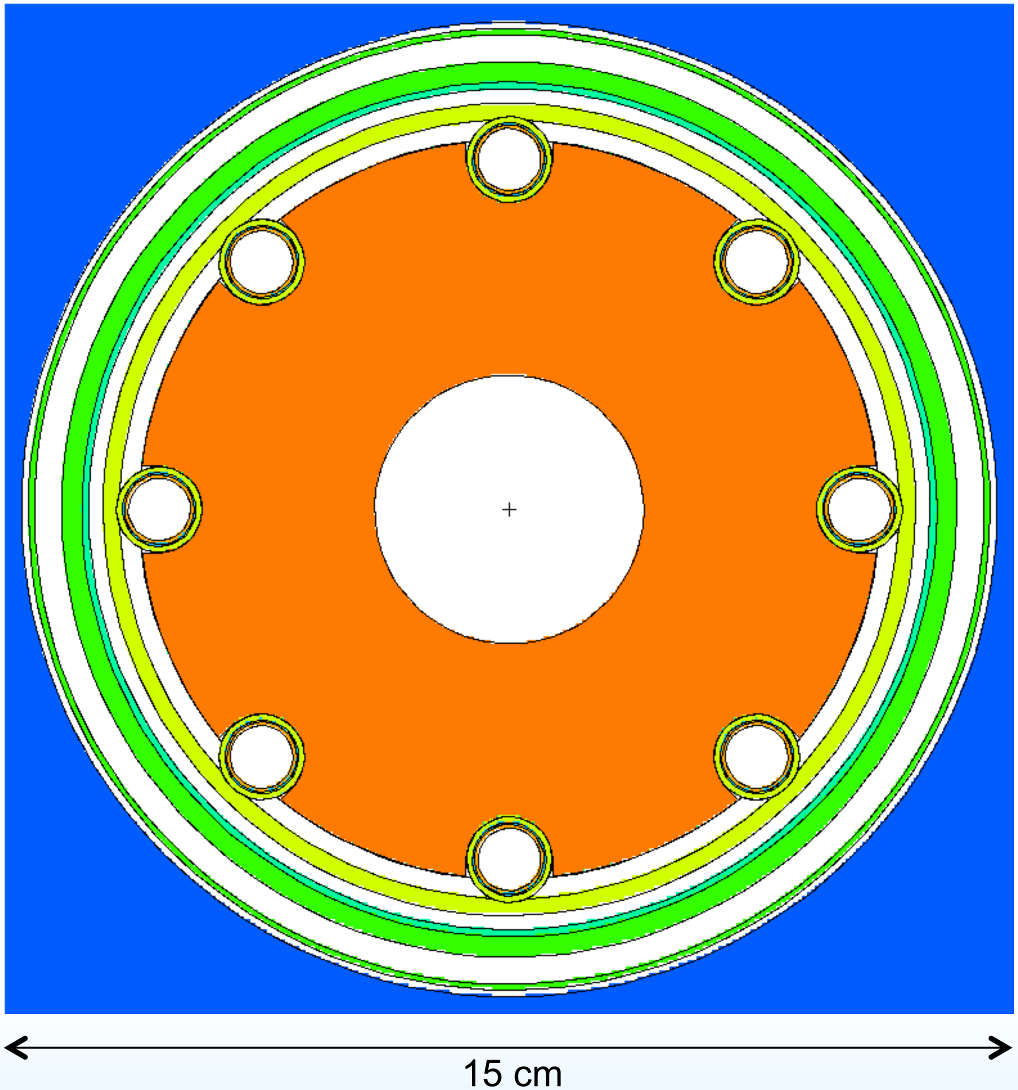
KRUSTY MCNP Model

See Godfroy Slides for Dimensions



Orange	U8Mo
Blue	BeO
Green	SS316
Yellow	B4C
Red	Al

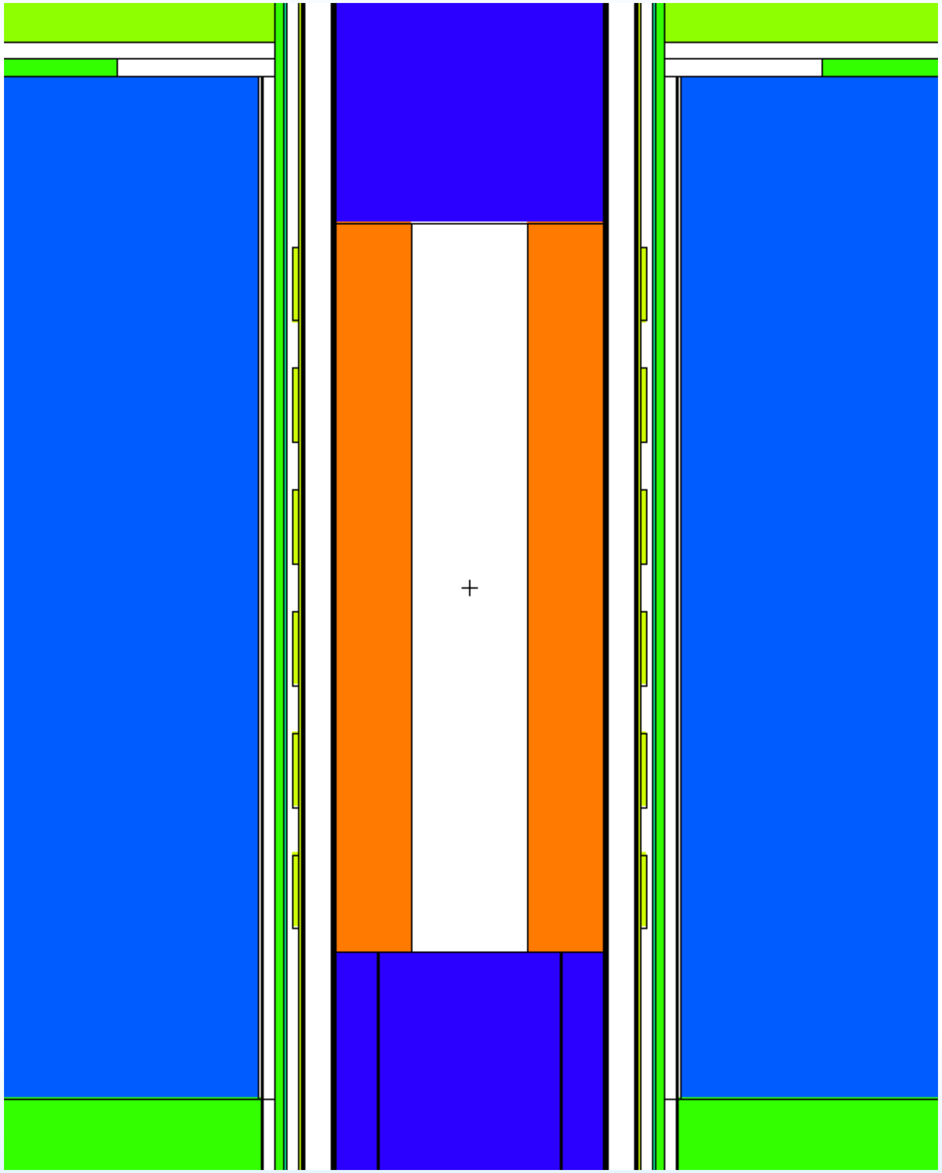
Core Model



Orange	U8Mo
Blue	BeO
Green	SS316
Light-green	Haynes230
Light-Blue	Mo multifoil

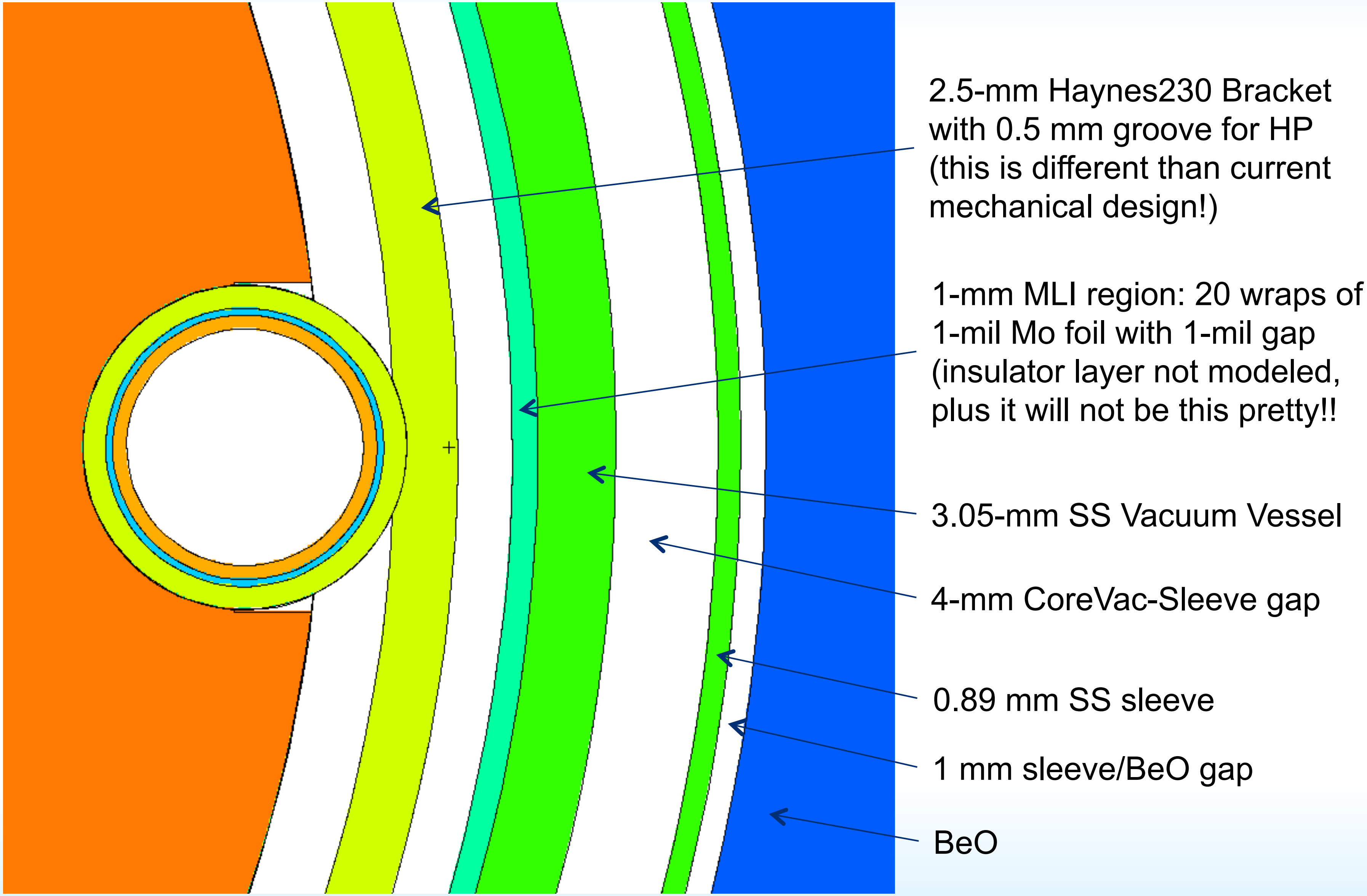
4.0	Central Hole OD (cm)
11.0	Core OD (cm)
10.4	HP "Ring" Dia (cm)
1.270	Heat pipe OD (cm) 0.625"
1.092	Heat pipe ID (cm) 0.035" wall
0.003	Fuel liner/can thickness (cm)
3.050	Corevac thickness (cm) 0.120"
12.700	Corevac ID (5”)
13.310	Corevac OD (.120” thick)
14.110	Radref Sleeve ID (cm)

KRUSTY Model



2.62	Fuel core L/D
25	Fueled length (cm)
35	Radref length (cm)
10	Top Axial Reflector length (cm)
10	Bot Axial Reflector length (cm)
32.7	Fuel mass (kg of U8Mo)
4.3	Axial Reflector mass
92.5	Radref mass

The KRUSTY "Divide"



Vessel, radref and core all thermally expand freely based on the input temperature to determine reactivity.

KRUSTY Nuclear Parameters

0.00001%	Fuel Burnup (FIMA)
2.17E+16	Fuel Burnup (fissions/cc)
0.00%	Fuel Swelling (Vol%)
2.15	Power density (W/cc)
1100	Core Ave Fuel Temperature (K)
92.00%	Uranium mass %
93.10%	U235 Enrichment %
98.00%	Fuel meat TD %
8.00%	Mo w/o
28.0	Total U235 Inventory (kg)
395	Radial Reflector average temp (K)
95.0%	Radref Be theoretical density
0.00%	Radref Be swelling
1.24E+12	Core Ave Neutron Flux (n/cm2-s)
4.95	Fuel fission-to-capture ratio (includes Mo)

Kilopower / KRUSTY Differences

- Differences for the reactor only

	Space 1-kWe Kilopower	KRUSTY	Mars 10-kWe Kilopower
Reactivity Control	Central poison rod	Comet lifts reflector	Central poison rod
Operating time	15 years	20 hours?	10 years
Lifetime Reactivity Control	No	n/a	Yes
Fuel/radref separation	1-mm	1-cm (the Divide)	1-mm
Core can/vessel	No	Yes	Yes
Reference heat pipe OD	3/8"	1/2"	5/8”
Heat pipe thermal bonding	Clamp force?	Clamp force	Braze?
U235 mass	28.4 kg	28.0 kg	43.7 kg
Core Length	24 cm	25 cm	28 cm
Shielding	LiH/DU shadow	SS/B4C 4pi	SS/B4C 4pi
Radref temperature	~700 K	~400 K	~700 K
Gravity	0g	1g	.38g

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- **KRUSTY Design sensitivities**
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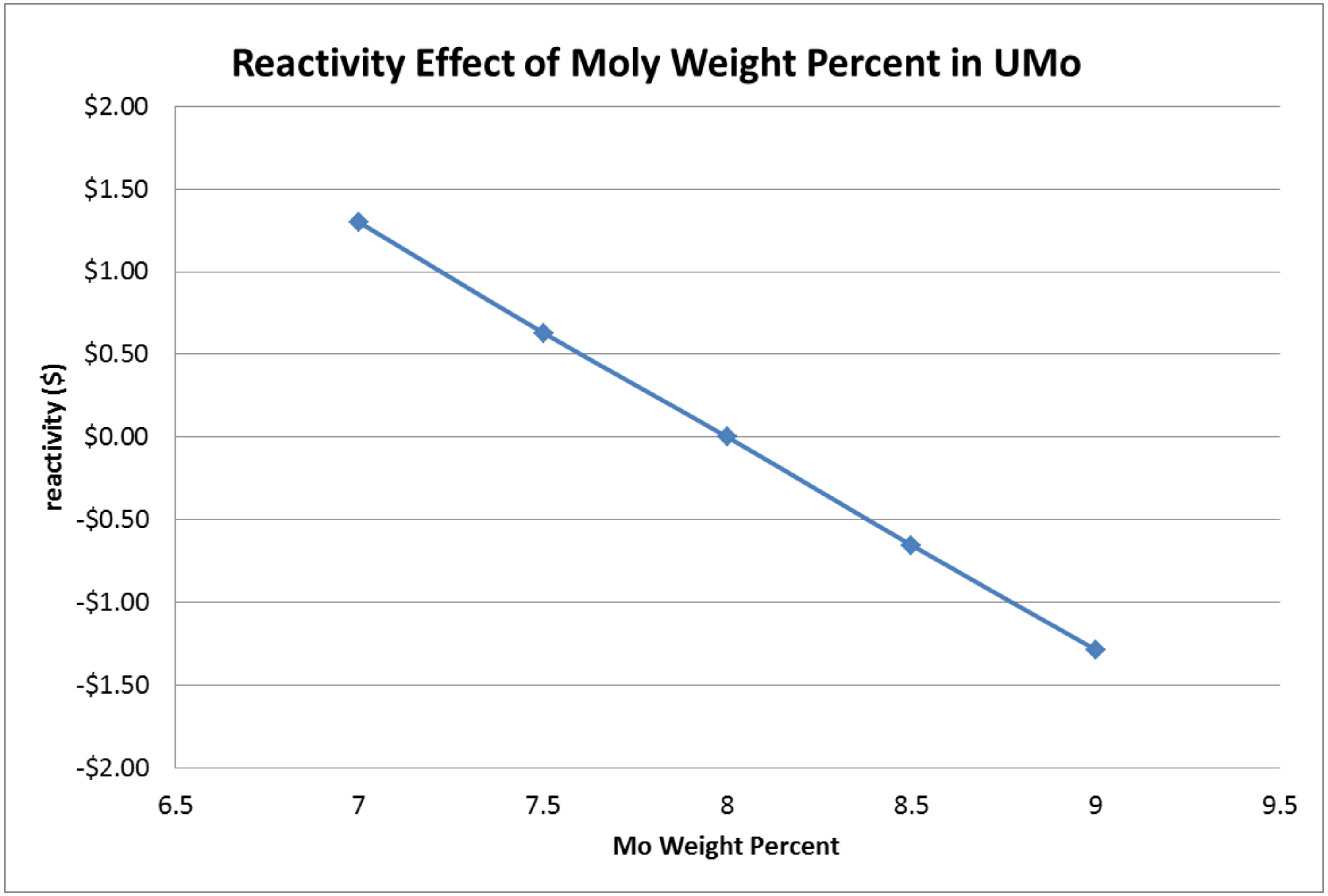
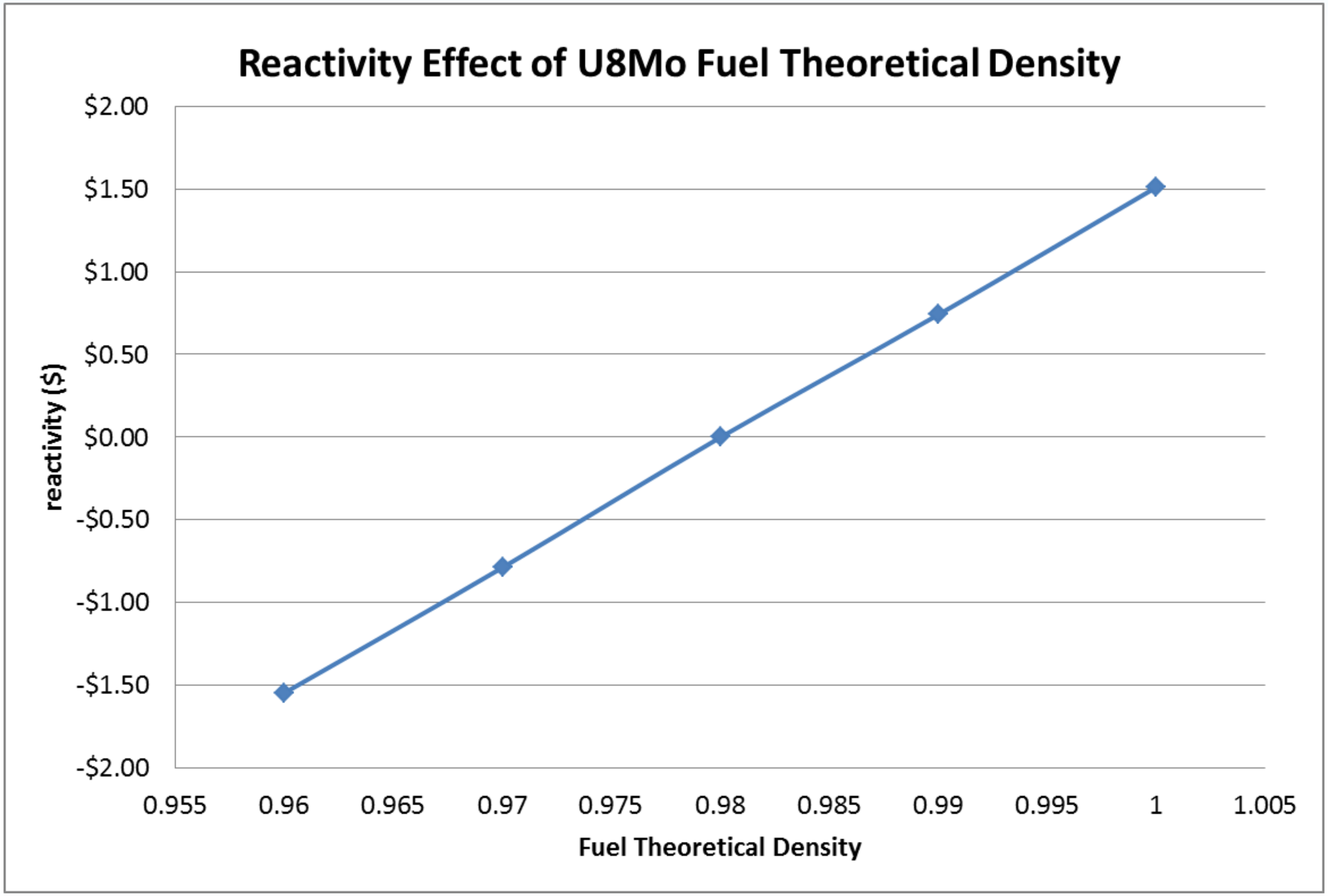
Fuel Moly Weight Percent



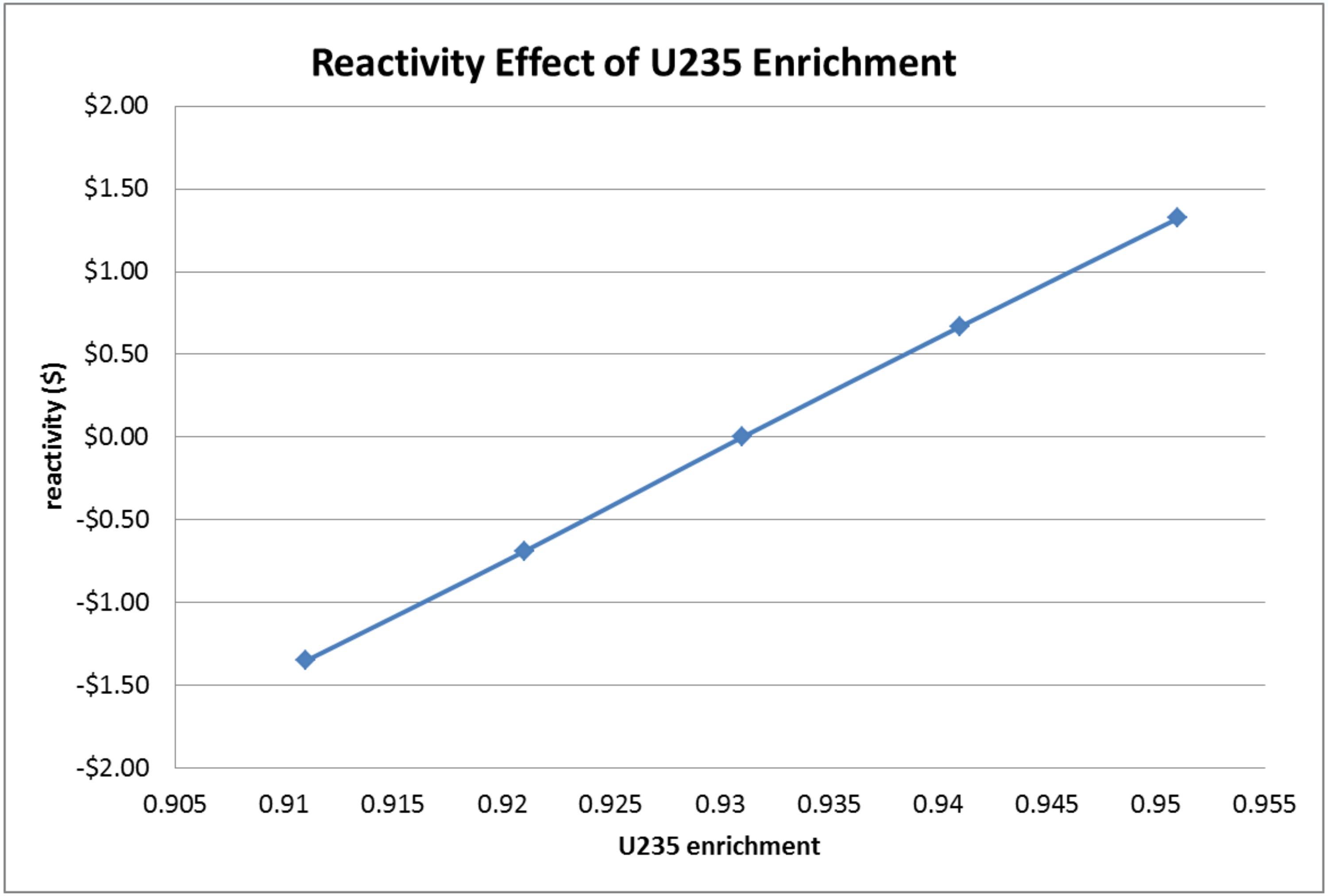
Every weight percent in Mo is worth about $1.3

Fuel Density



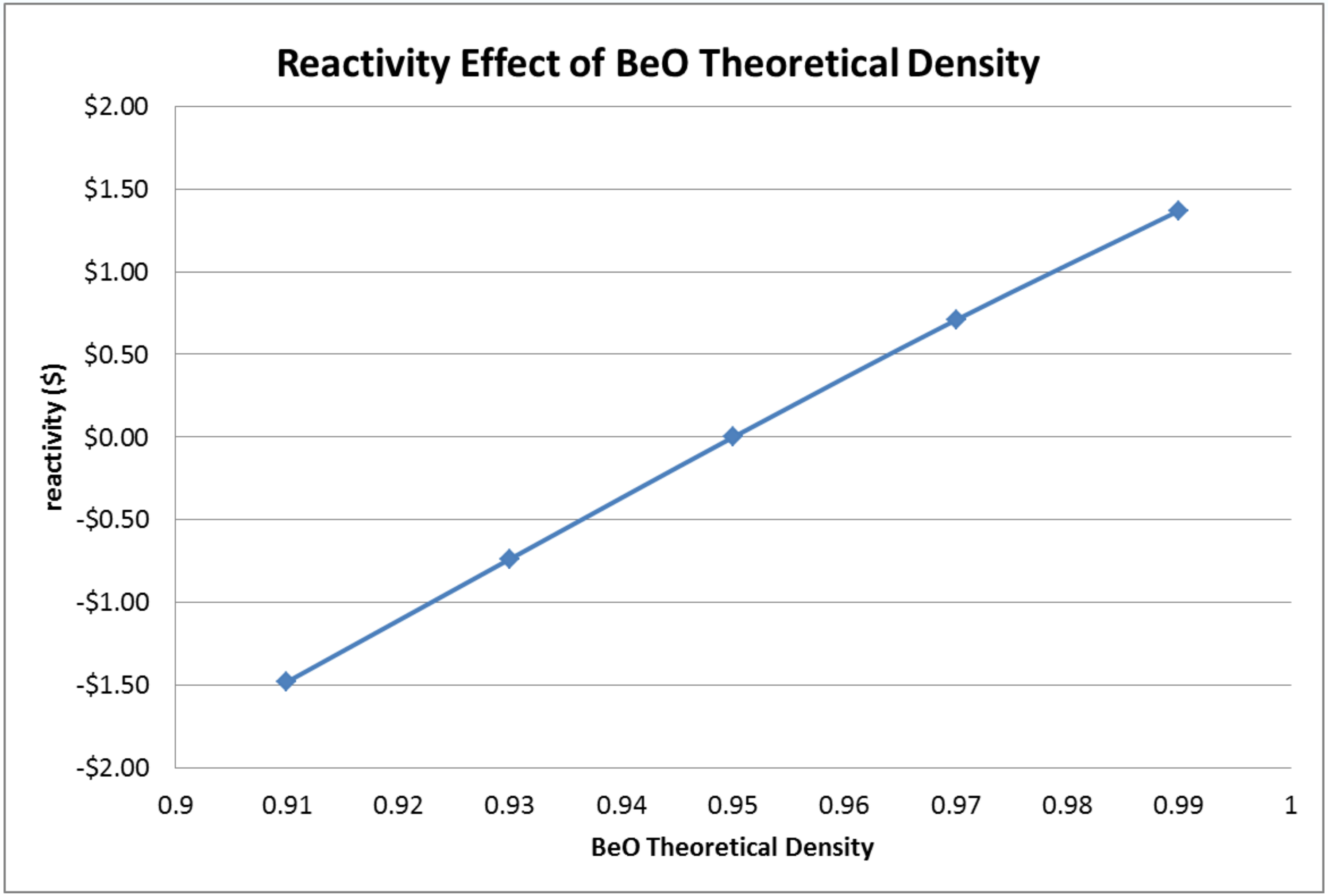
Every percent in fuel T.D. is worth about 75 cents.

U235 Enrichment



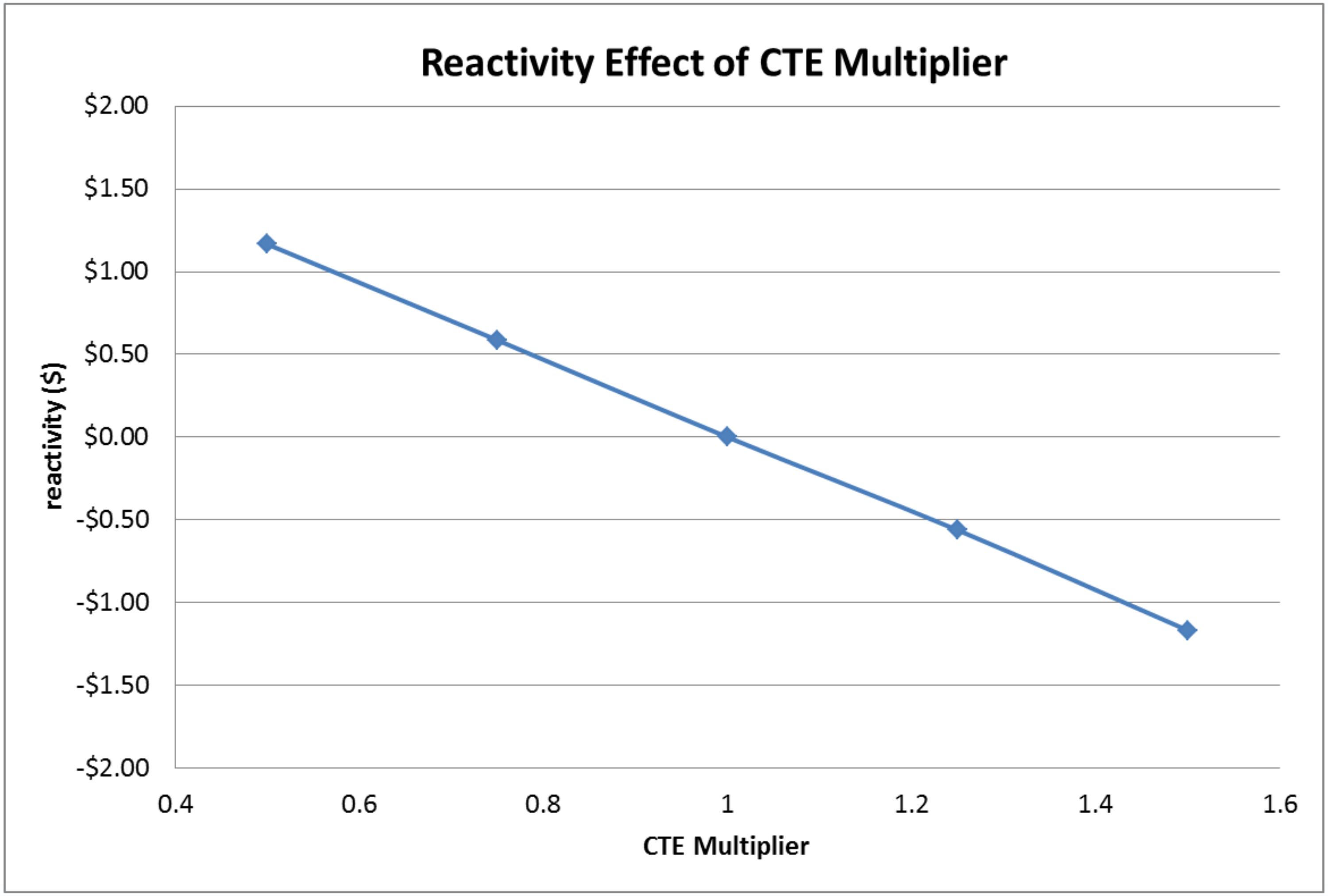
Every percent in enrichment is worth about 65 cents.

BeO Density



Every percent in BeO T.D. is worth about 35 cents.

Changes in Fuel CTE

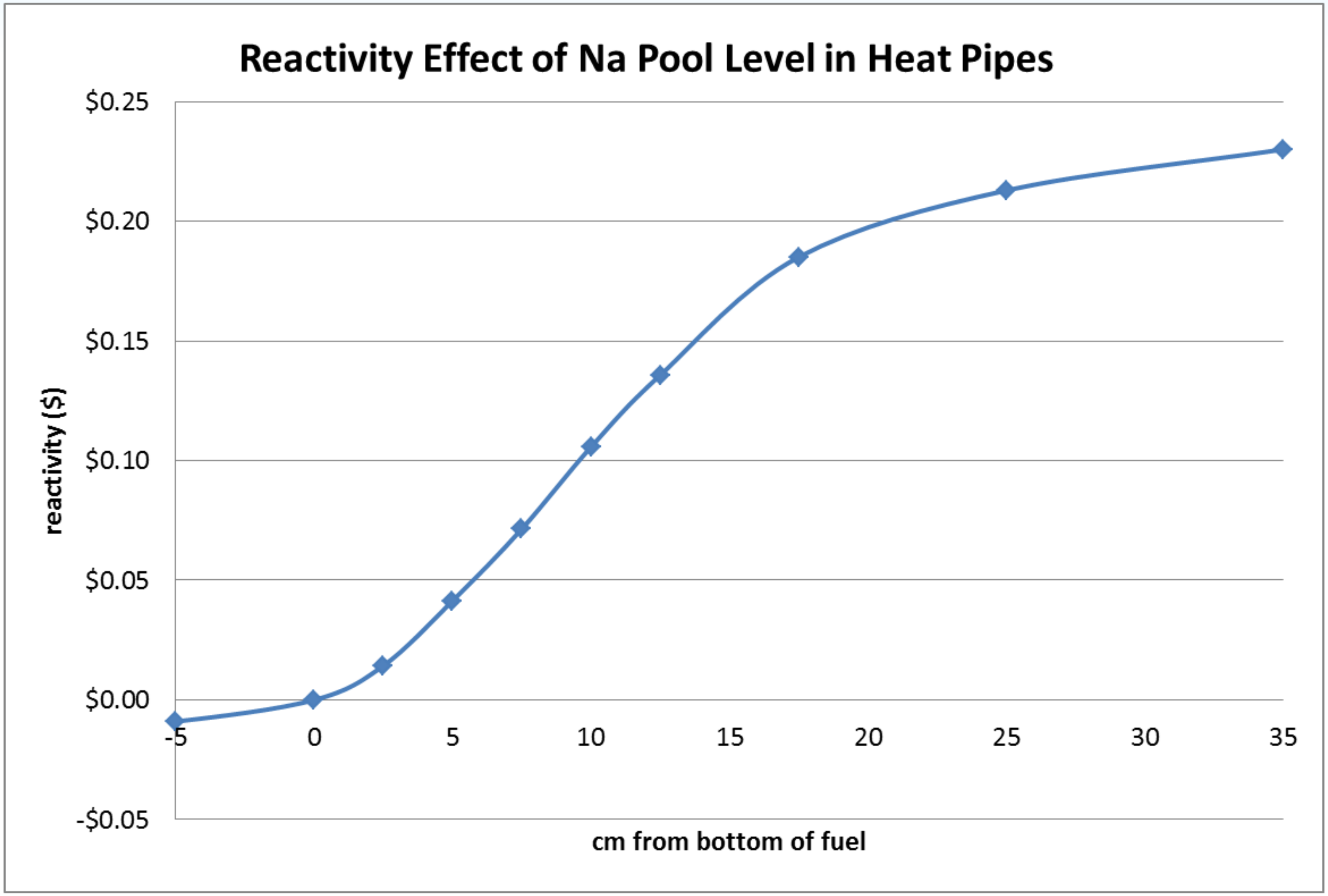


MRPLOW CTEs (1x)

300	11.5
350	12.1
400	12.8
450	13.4
500	14.0
550	14.6
600	15.2
650	15.8
700	16.4
750	17.0
800	17.6
850	18.2
900	18.8
950	19.4
1000	20.0
1050	20.6
1100	21.2
1150	21.8
1200	22.4

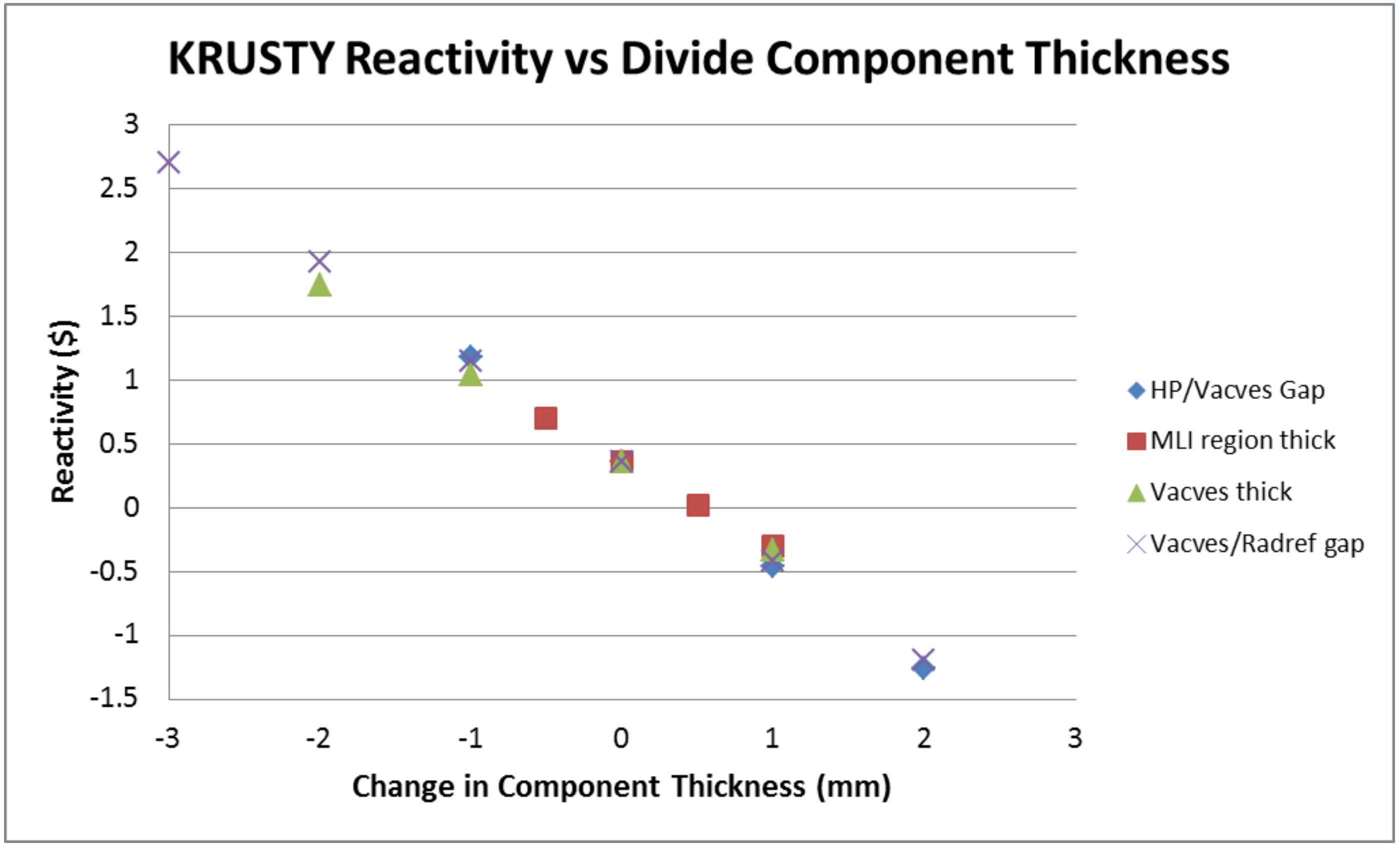
If CTE is 25% higher than current model it will drop warm reactivity by $.60, or vice versa.

Sodium Pool Level



The level of Na in the HPs is tbd, which will slightly impact keff. More important is the potential change in level as the HP warms-up/turns-on. The redistribution of Na will depend on how thick the wick and arteries are, and how much the HP performs like a thermosyphon.

Possible Future Reactivity Change: Size of the Divide



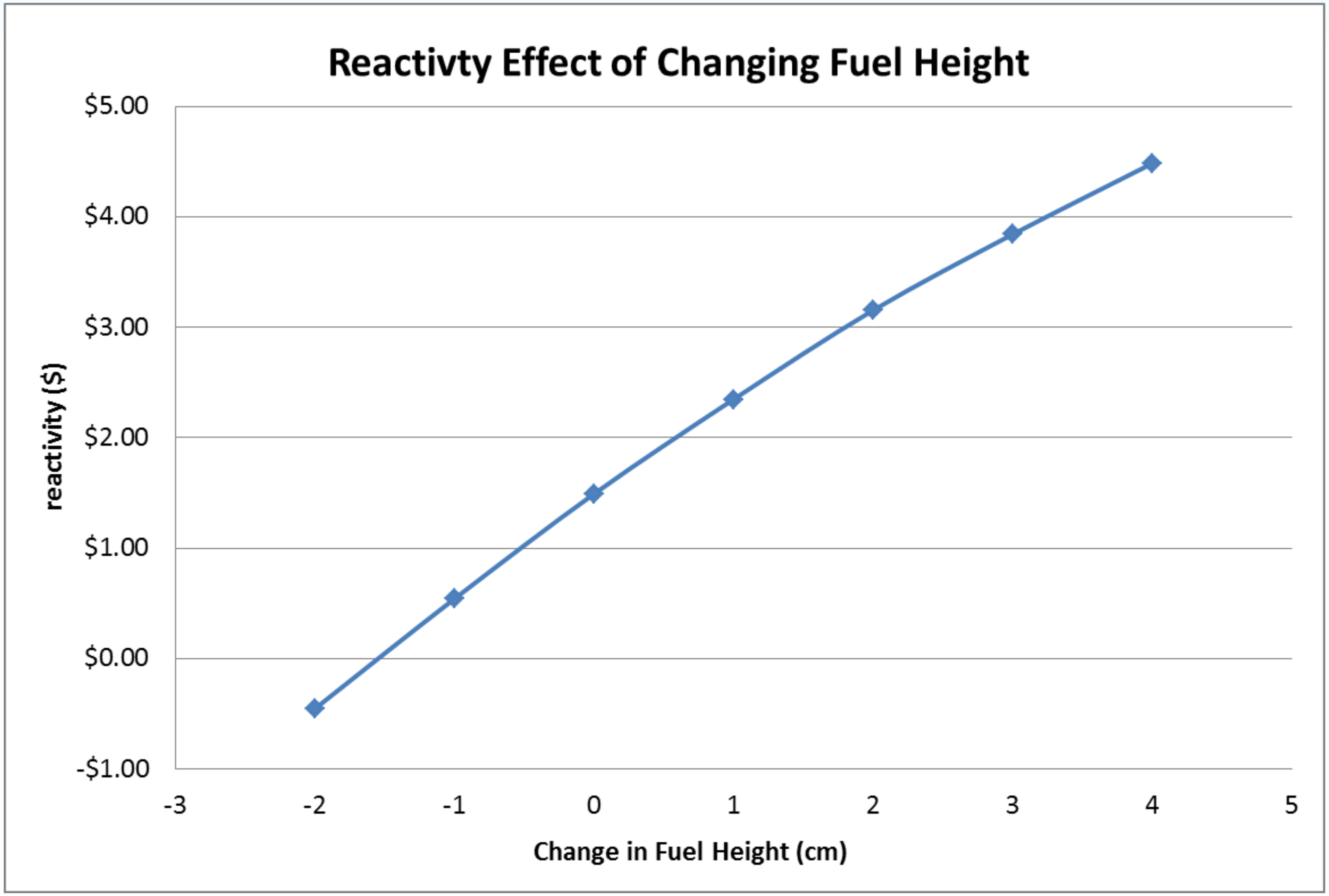
Reactivity is very sensitive to every millimeter of the Divide, about 75 cents per mm. What's interesting is that it makes almost no difference is there is mass in the Divide or void. In general the increased reflection balances our any increase absorption.

Note: This is for an older design, and will be different (likely smaller) with the current highly reflected design).

Modeling Errors/Biases

- DUFF was nailed very well, but it was almost all uranium AND there was prior data to benchmark with (the HP, notably the water in the HP was the only significant difference),
- KRUSTY has a very high worth BeO reflector, and some past studies have indicated that the cross sections may not be very good in this scenario.
- There is also some uncertainty of what the temperature of various components will be, positional tolerances, etc.
- My guess would be that the 1-sigma uncertainty for modeling this experiment if $0.50.
  - The current model has $1.50 of margin, which would allow for a 3-sigma type of miscalculation.
  - The other possible reactivity changes – fuel TD, Mo w/o, cte, etc. should be things we learn long before the test, and can accommodate for if needed by making the fuel a little longer or shorter.

Core Length



The is for the fully inserted, full BEO-stack condition; thus the nominal case is our current $1.50 margin. The first cm adds about $0.85, with diminishing returns

This calculation keeps the overall reactor dimensions the same, but replaces BeO axial reflector with fuel (so instead of 25 cm fuel with 10 cm axref each side you might have 27 cm of fuel with 9cm of axref on each side – all other dimensions remain the same)

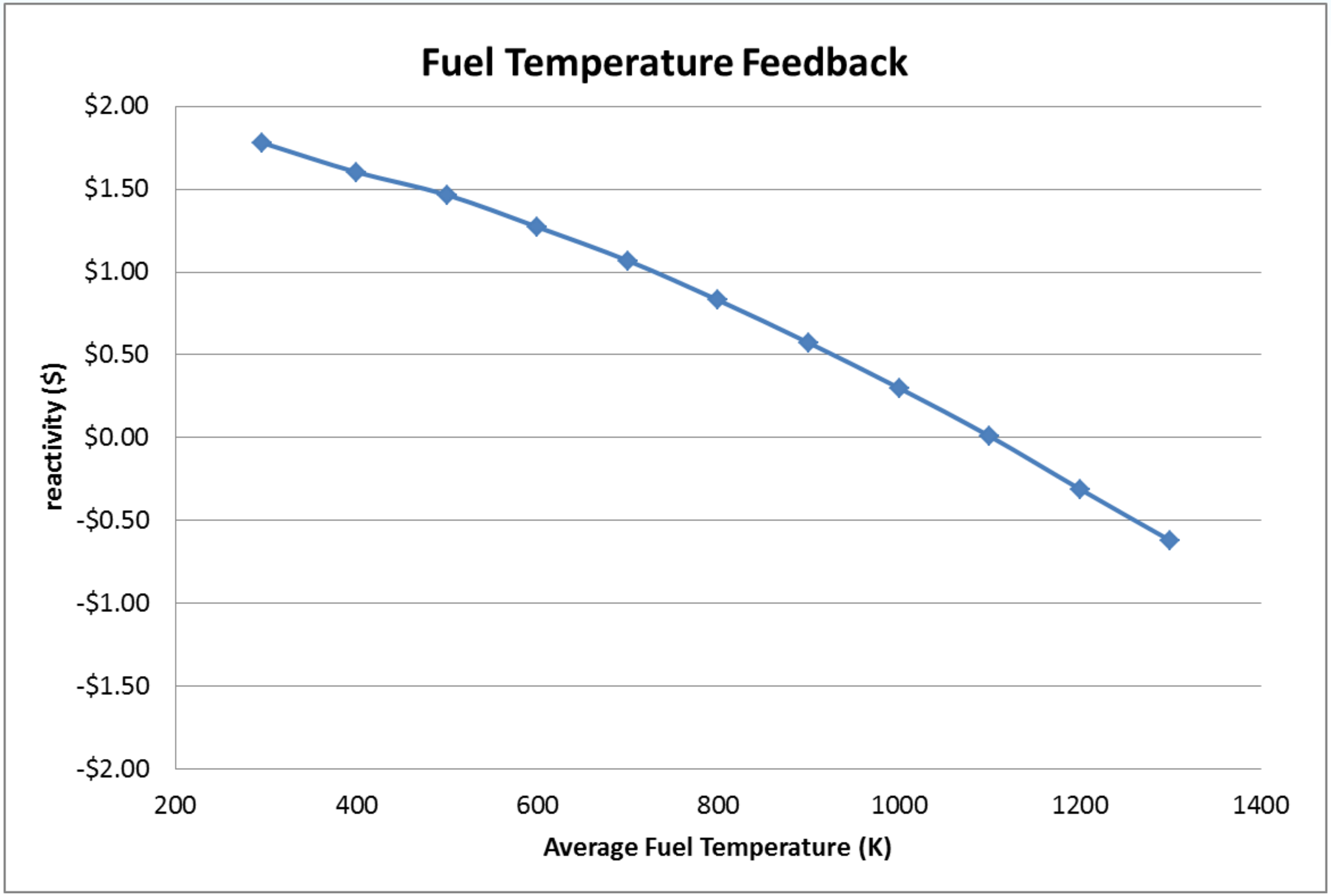
Topics Covered

- Reference Kilopower configuration
- Reference KRUSTY configuration
- KRUSTY Design sensitivities
- **KRUSTY Reactivity Coefficients**
- KRUSTY Criticality safety and control
- KRUSTY Core activation/dose
- KRUSTY Shielding, room activation/dose

KRUSTY Reactivity Coefficients

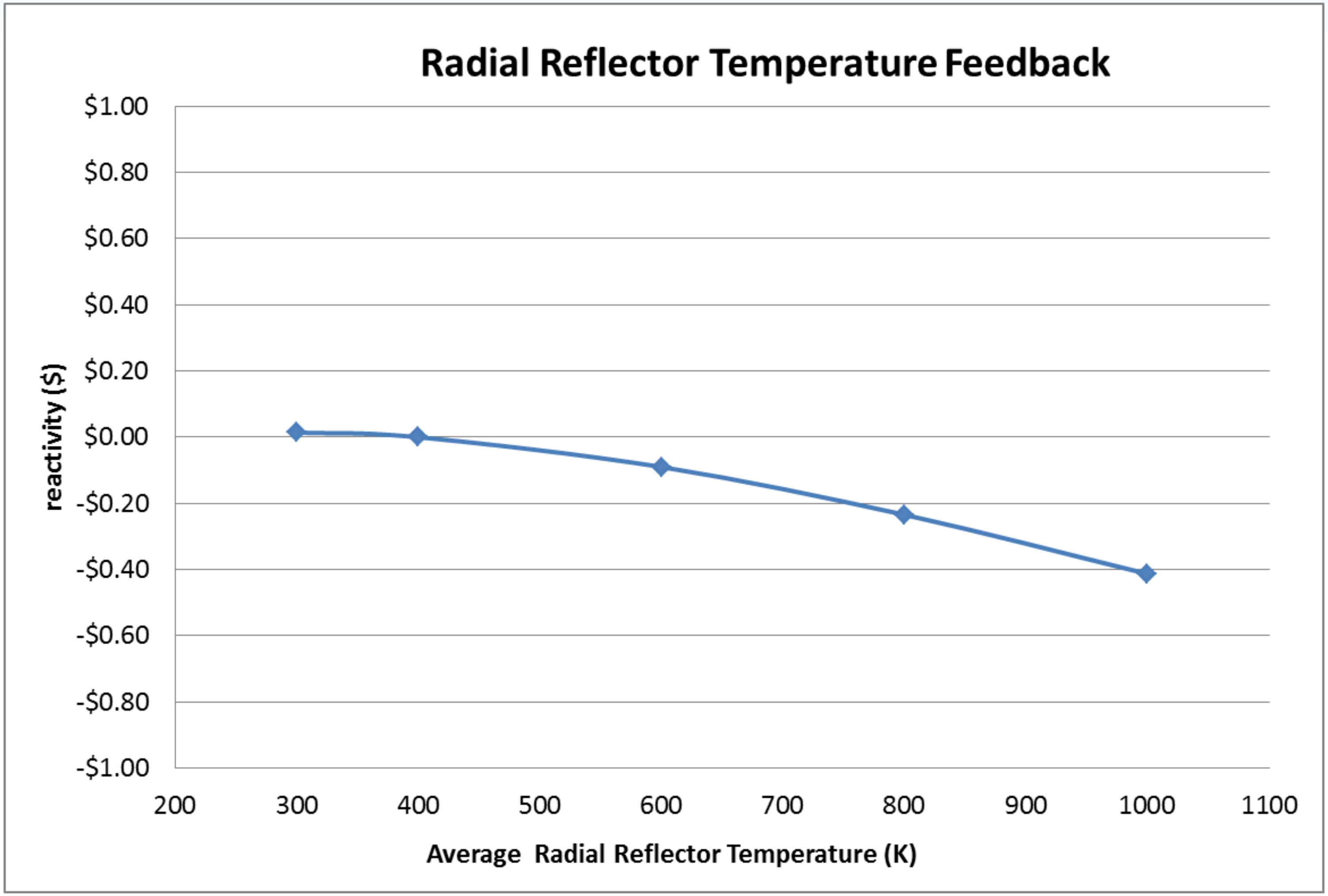
- Material Movement
  - A major concern with compact-fast reactor is fuel/pin movement relative to other fuel.
    - KRUSTY fuel is in 3 large pieces that are tightly constrained radially, so this removes a major uncertainty.
    - Gravity and the heat pipes should keep the pieces together in the axial direction
  - Movement of fuel radially relative to vacuum vessel and reflector should have negligible impact
  - Movement of fuel axially relative to vacuum vessel and reflector should have negligible impact.
- Coolant (Na) Reactivity
  - Changes in Na temperature and density have a negligible impact; however a change in the pool height is noticeable (~1 cent/cm)
    - As noted earlier. It is not anticipated that the pool height will change more than a few cm from cold to operating condition.

KRUSTY Reactivity versus Core Temp



Reactivity drop is almost entirely a function of expansion, and thus the fuel material CTE (which becomes greater at higher temperature), cross sections are a secondary factor. This calculation assumes cold vessel and radref.

KRUSTY Reactivity versus Radial Reflector Temperature



Reactivity drop is a function of expansion (BeO CTE is also greater at higher temp) and change in scattering energies with temp. Effect much lower than Kilopower due to the Divide and the thick SS316 shield. Flat feedback from 300 to 400 K is likely because reactivity loss due to expansion is offset by gain due to less thermalization (less parasitic capture by vessel/brackets)

Reactivity Coefficients

- Fuel RTC
  - -0.23 cents/C – average from room temp to operating
  - -0.15 cents/C – instantaneous at room temp
  - -0.32 cents/C – instantaneous at operating temp
- Radial Reflector RTC
  - -0.00 cents/C – instantaneous at room temp
  - -0.09 cents/C – instantaneous at 900 K
- Average vacuum vessel/clamp RTC
  - -0.01 cents/C

The behavior of the fuel RTC is very nice (assuming the fuel CTE behavior is correct), because you'd rather have a higher RTC up near operating temp, and a lower one at startup temp.

The clamps provide a reactivity wild card. Will they be pushed out by the fuel/HPs, constrain the fuel, or push the HPs into the fuel? The above calculations assume that the fuel and claps expand freely relative to each other. Overall the impact should be small, and we will get a good idea of how things move during non-nuclear testing.

Topics Covered

- Reference Kilopower configuration
- Reference KRUSTY configuration
- KRUSTY Design sensitivities
- KRUSTY Reactivity Coefficients
- **KRUSTY Criticality control and safety**
- KRUSTY Core activation/dose
- KRUSTY Shielding, room activation/dose

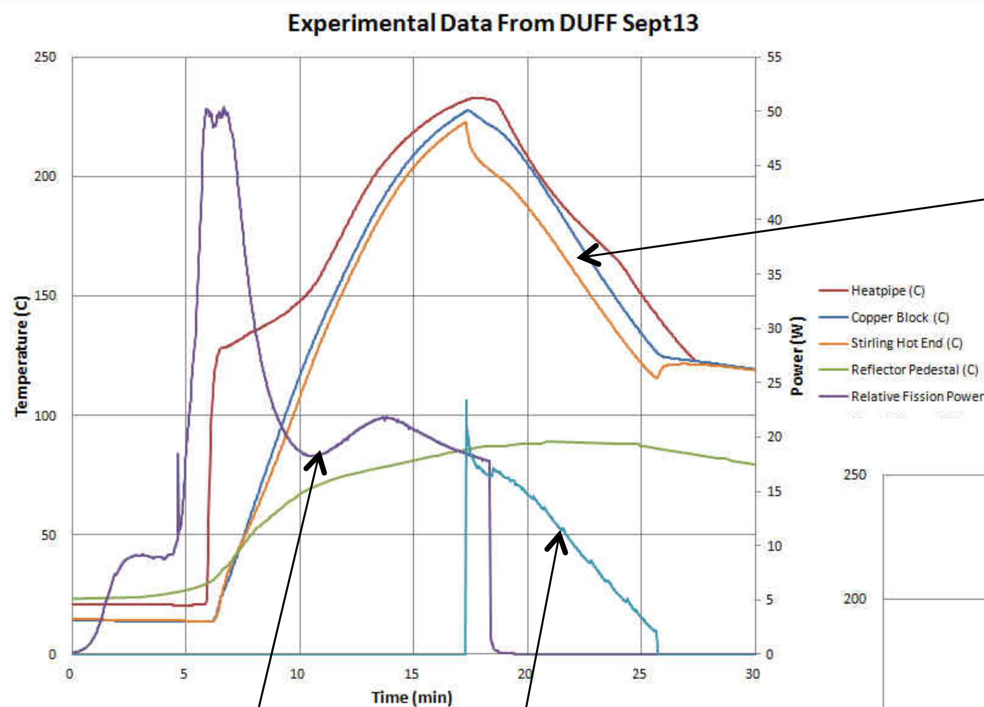
Criticality Safety of Core

- From a crit safety perspective, the KRUSTY core is neutronically similar to the Flattop HEU core.
- Keff calculations are shown below.

	bare	water	sand	wet-sand
krst1g assembled fuel	0.5983	0.9658	0.8404	0.9434
Flattop HEU core ball	0.6576	0.8991	0.8166	0.8863

  - Calculations use infinitely reflected: distilled water and 65% pure quartz (wet sand is lower then water).
  - Results will be lower for the 3 core sections, prior to joining
- There is no material that the core could be accidentally surrounded by that would take it critical other than Be or another fissile material (fully encased in 1m thick of form fitting high density graphite might do the trick).

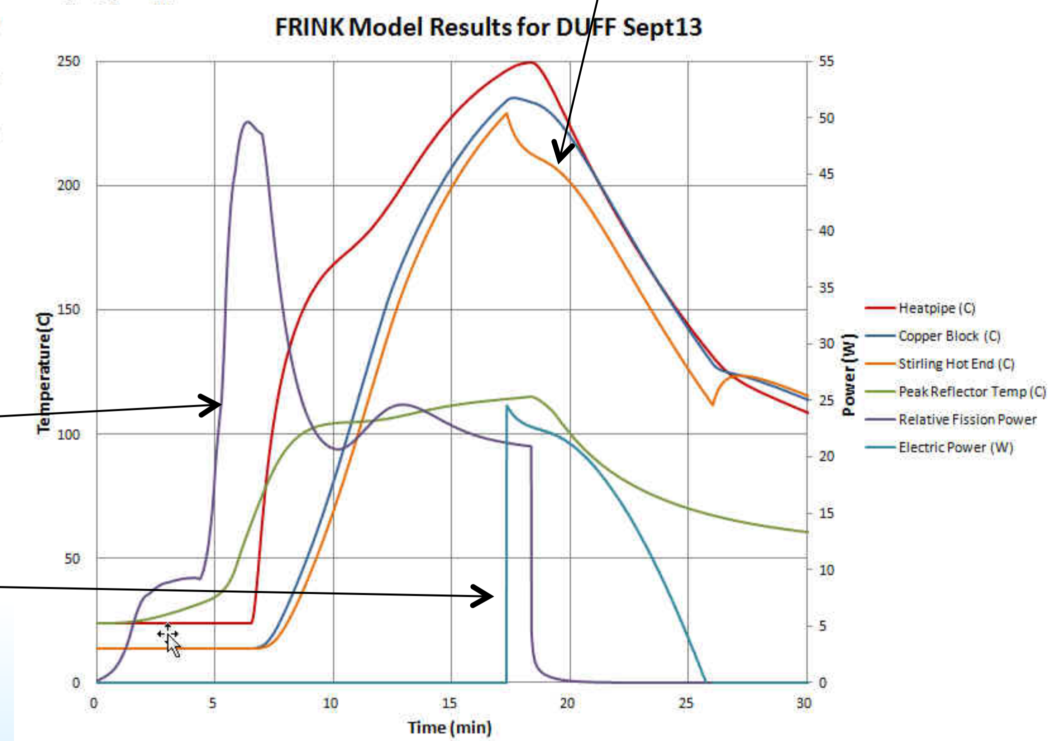
DUFF Run 1 Test Sequence/Results



Power Conversion System Temperatures

Reactor Thermal Power

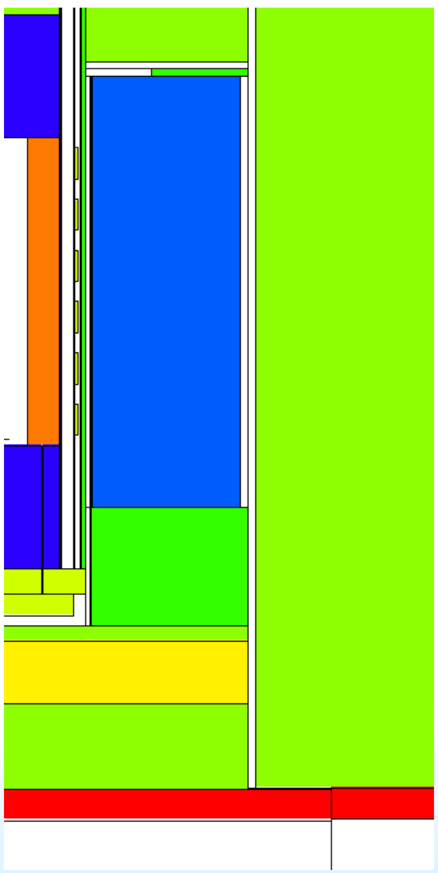
Electric Power



Definition of Positions

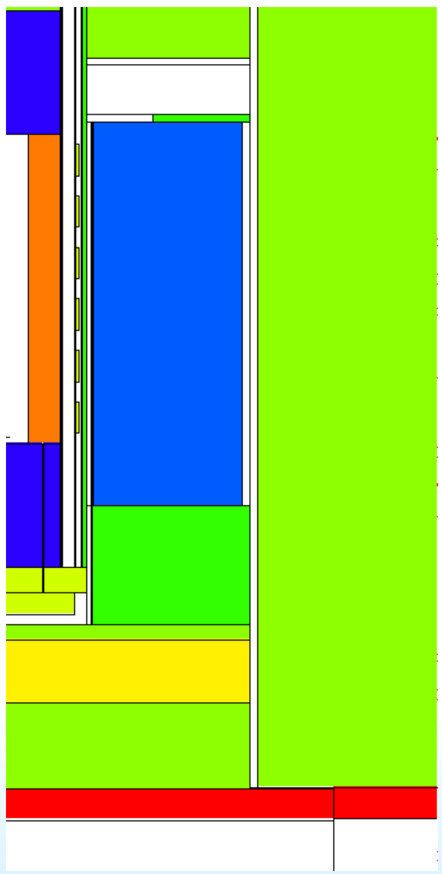
Fully inserted and fully stocked with BeO

Ztable = 0 cm
Shortstack = 0 cm



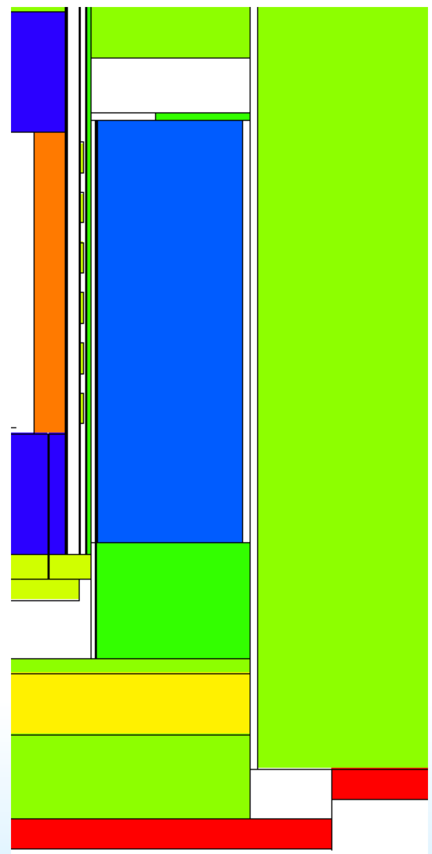
4 cm of BeO removed from stack

Ztable = 0 cm
Shortstack = -4 cm



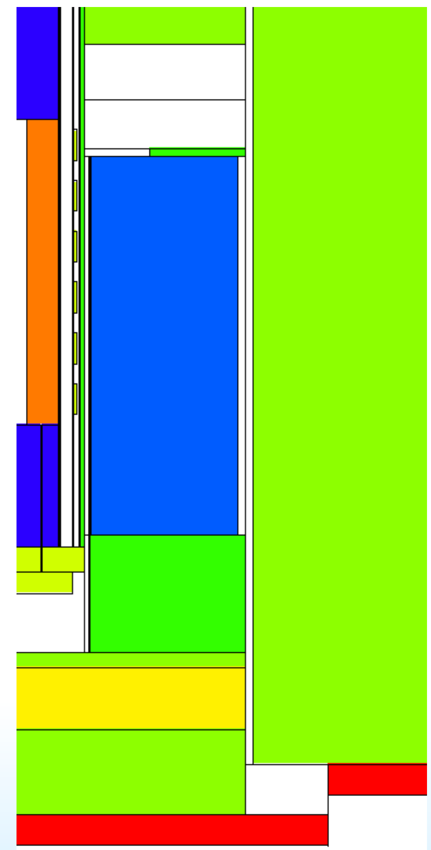
Platen withdrawn 4 cm

Ztable = -4 cm
Shortstack = 0 cm

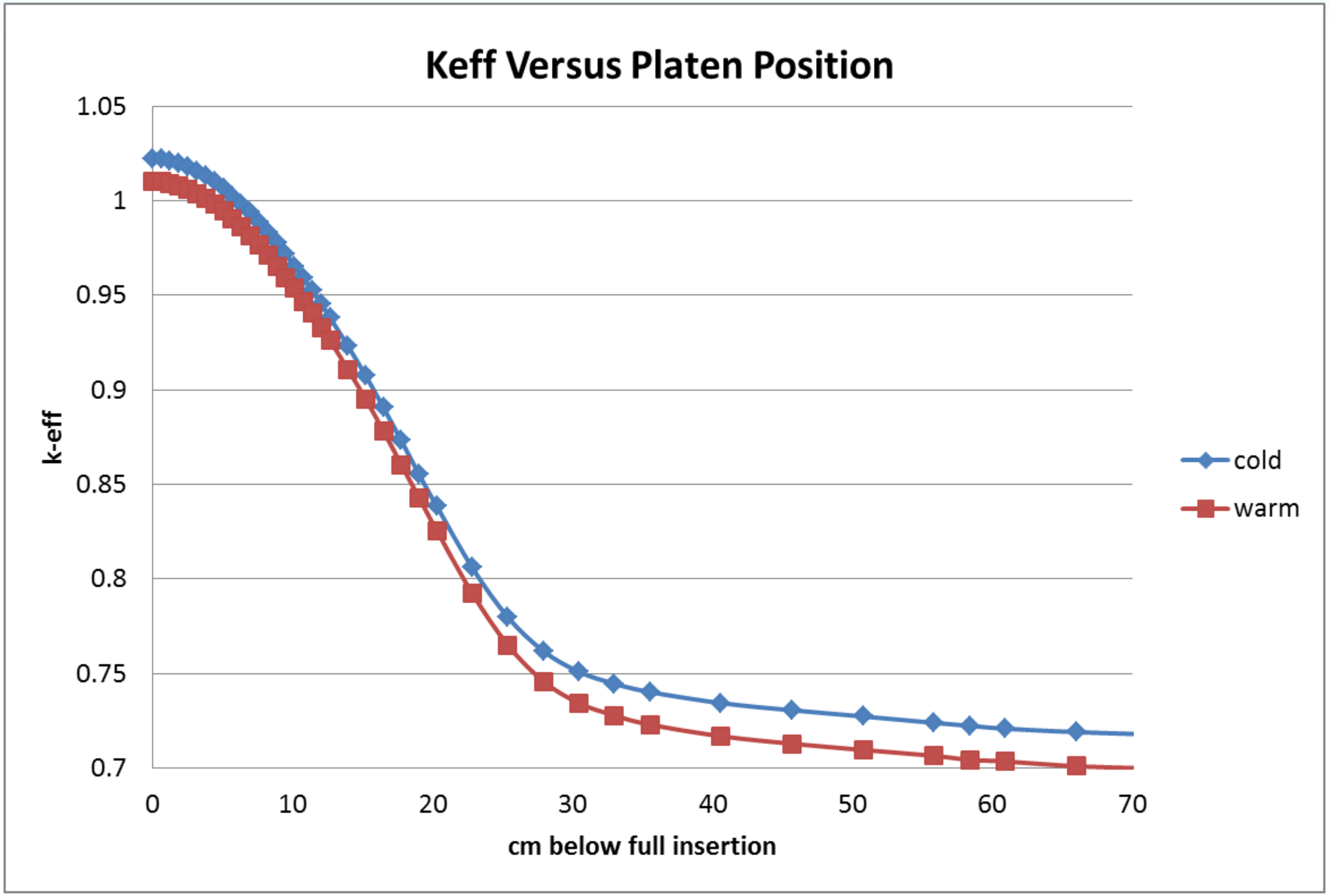


4 cm of BeO removed from stack and platen withdrawn 4 cm

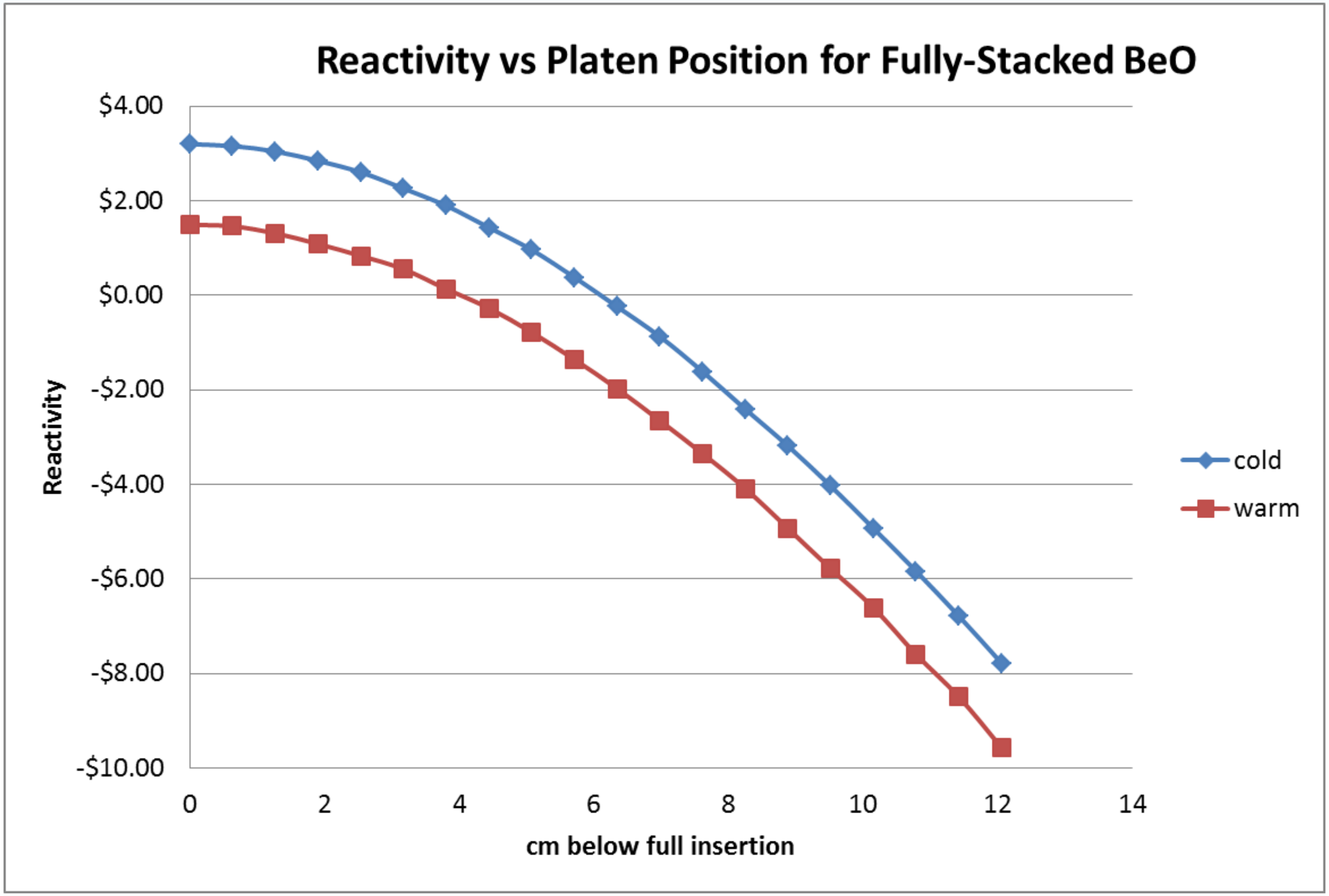
Ztable = -4 cm
Shortstack = -4 cm



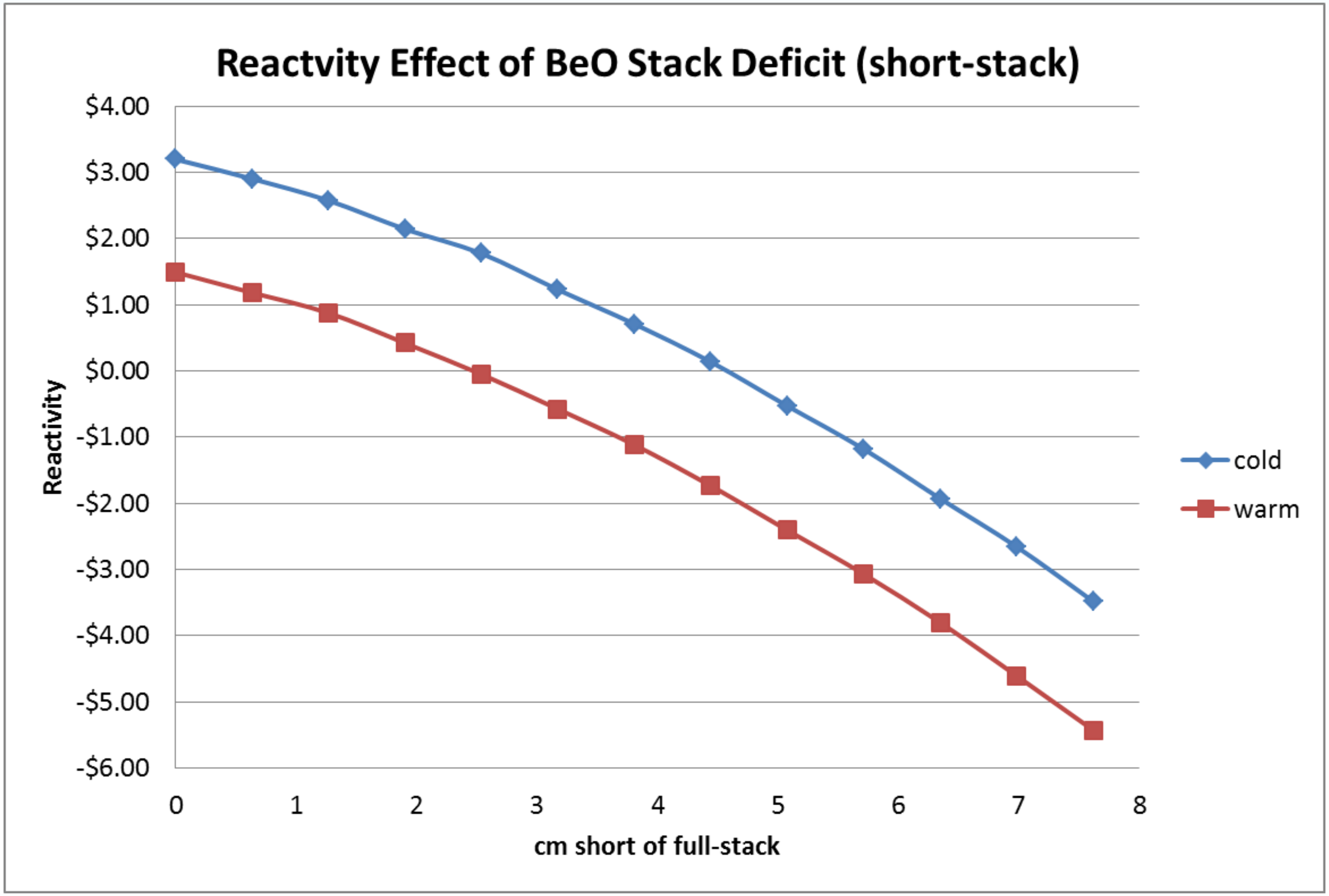
Nominal Fully-Stacked BeO Condition



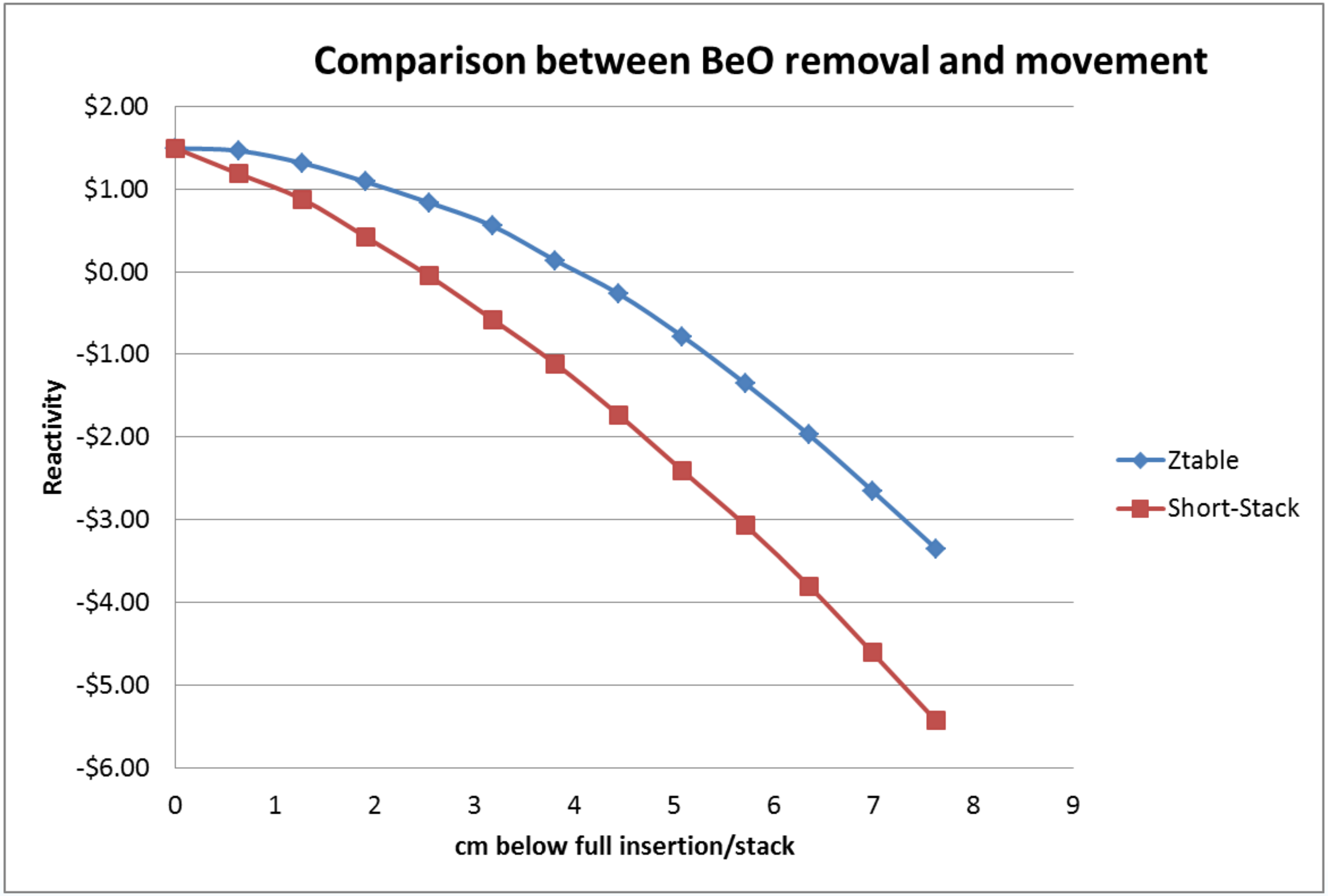
Effect of Platen Position



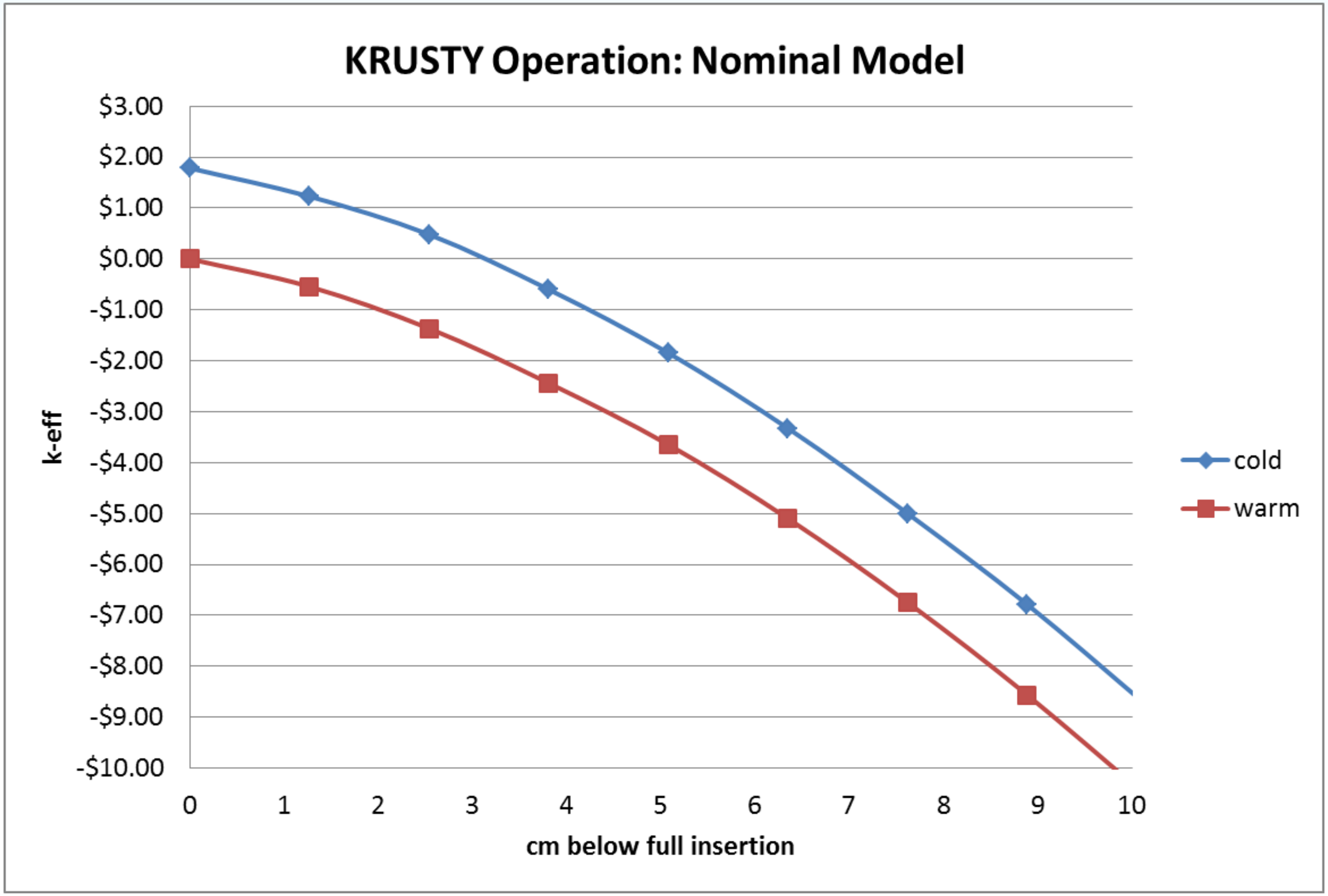
Effect of BeO Stack Height



BeO removal much more effective than movement

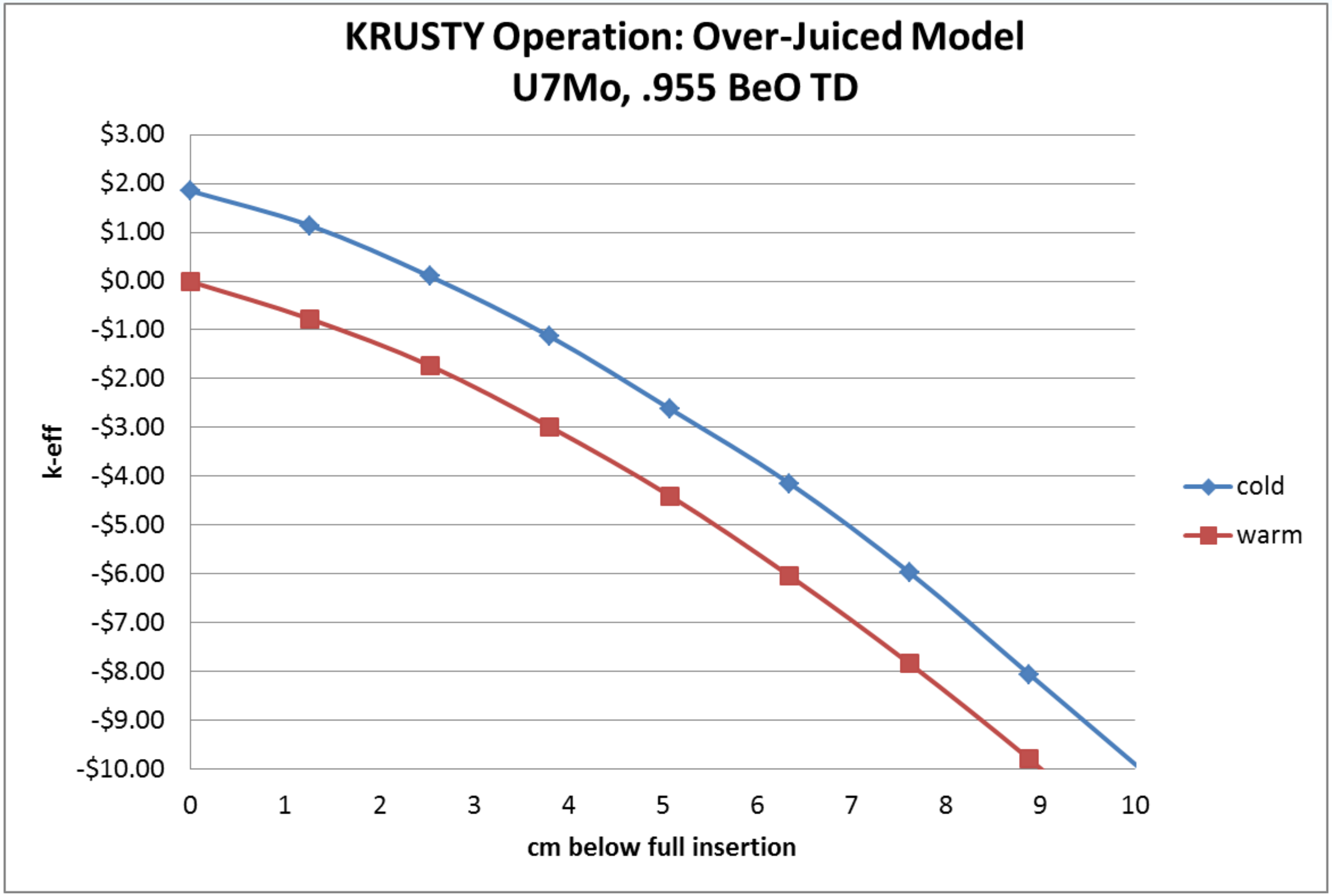


Full-Power Run: Nominal Model



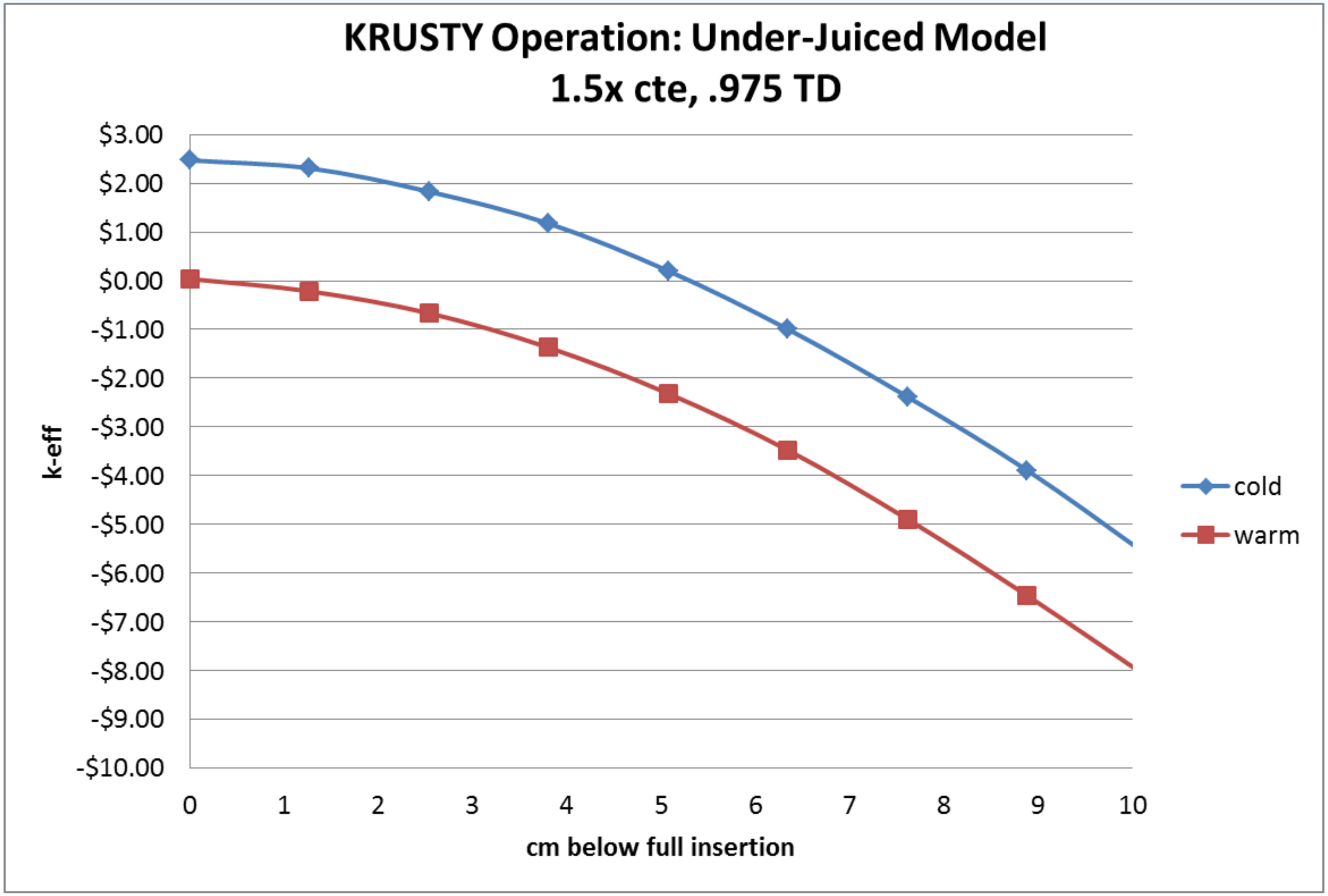
This assumes that the current model is correct, and the exact loading of BeO (short-stack=2.47 cm) had been predetermined from previous criticality runs.

Full-Power Run: Over-juiced Model



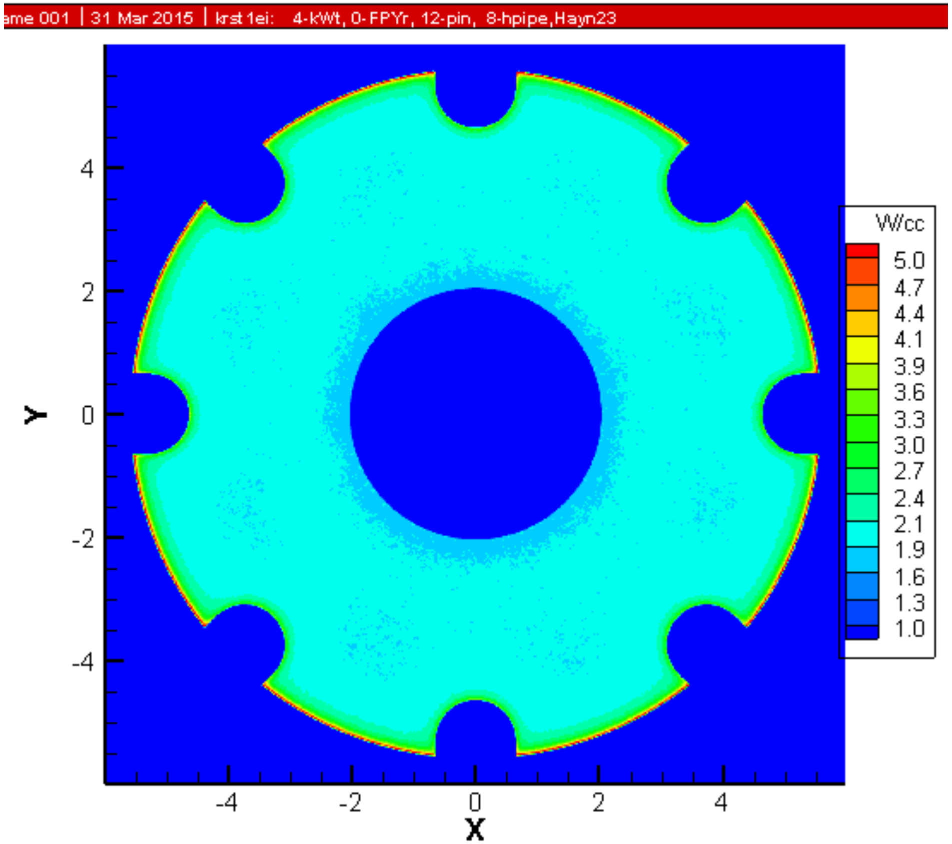
This assumes that we have more reactivity than the current model predicts (in this example U7Mo vs U8Mo and .955 TD BeO vs .95), and the exact loading of BeO (short-stack=4.03) had been predetermined from previous criticality runs.

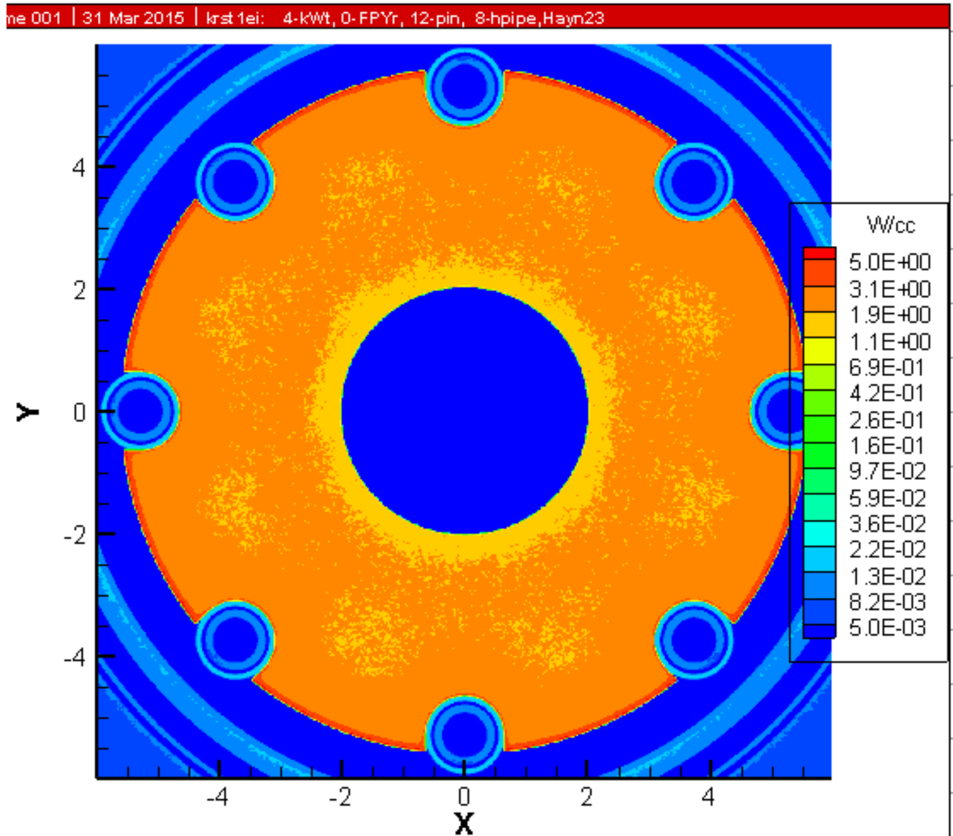
Full-Power Run: Under-Juiced Model



This assumes that the current model had over-predicted reactivity (in this case the CTE was larger and the fuel TD was lower) and fortunately we had just enough BeO (short-stack=0) to remain critical at operating temperature.

Radial Core Power Deposition

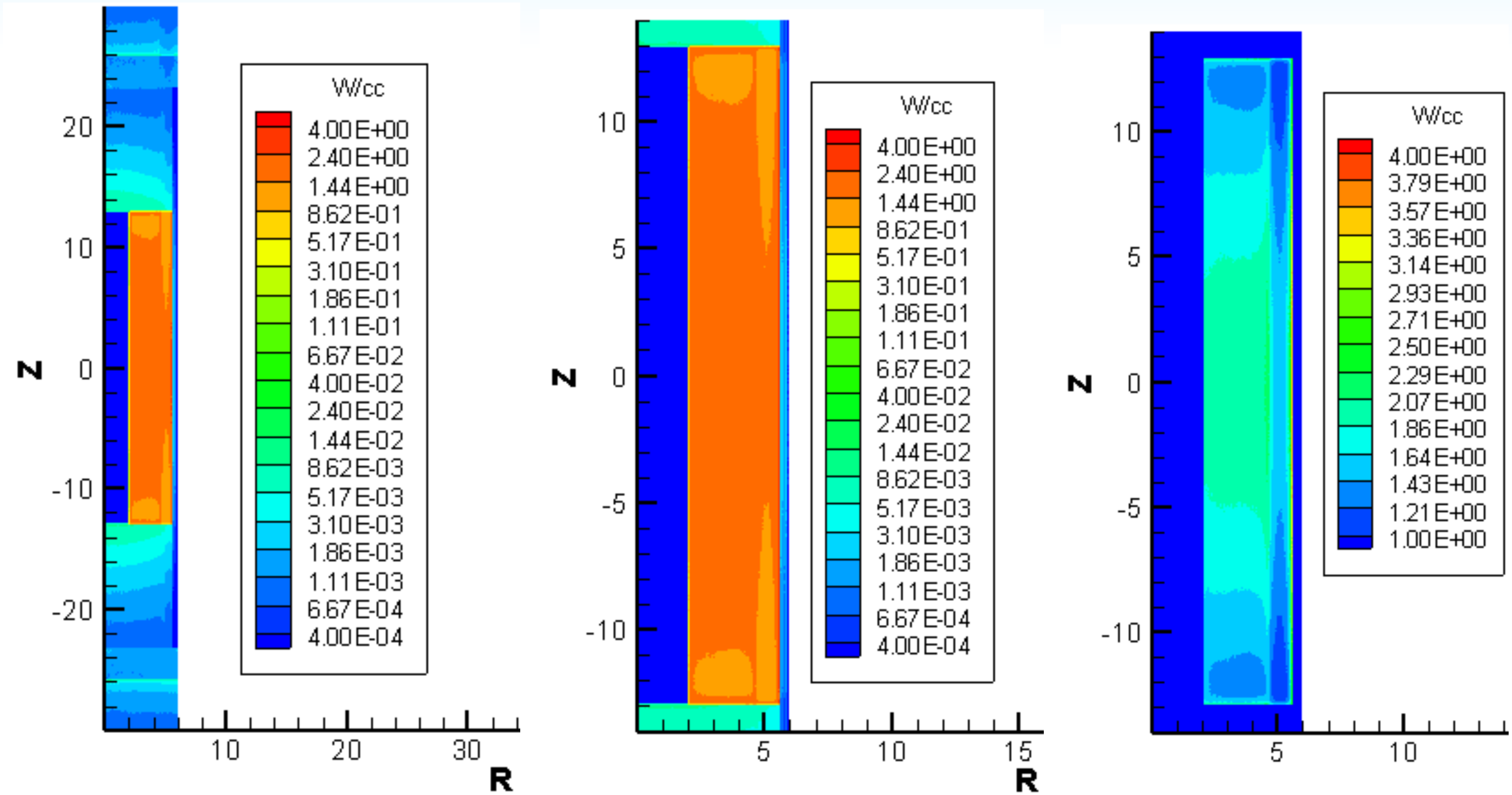




Good news is that power is tilted outward, which reduces delta-T in the nuclear test. Bad news is that it is significantly different than resistant heated, which puts 100% on the inside (which is more conservative than we'd like)

Note: this is krst1f, slightly different than krst1g

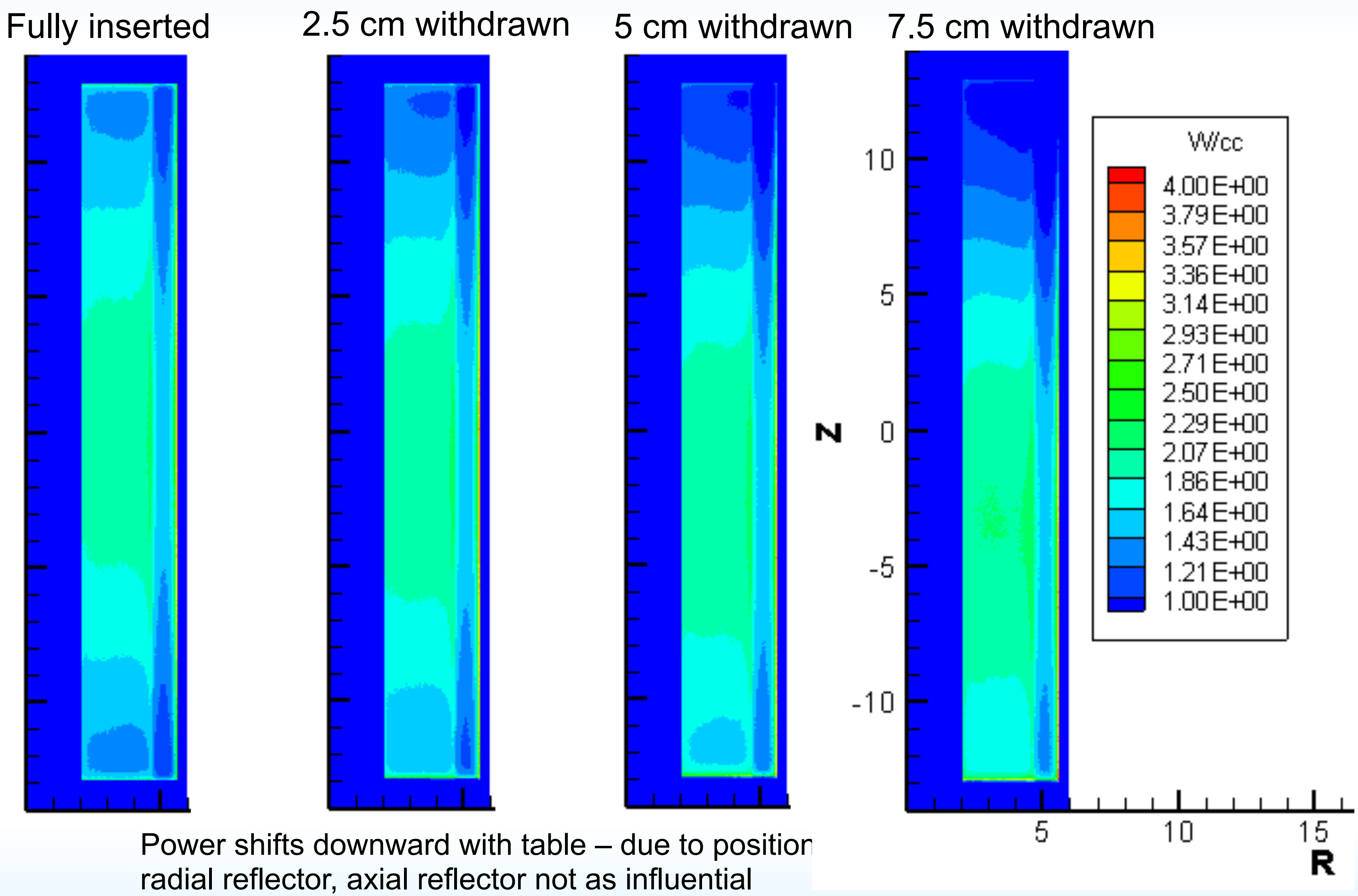
Axial Power Deposition



This is a r-z plot over the entire 360 degree azimuth, thus is gets squirrelly once you hit the heat pipe region.

Note: this is krst1f, slightly different than krst1g

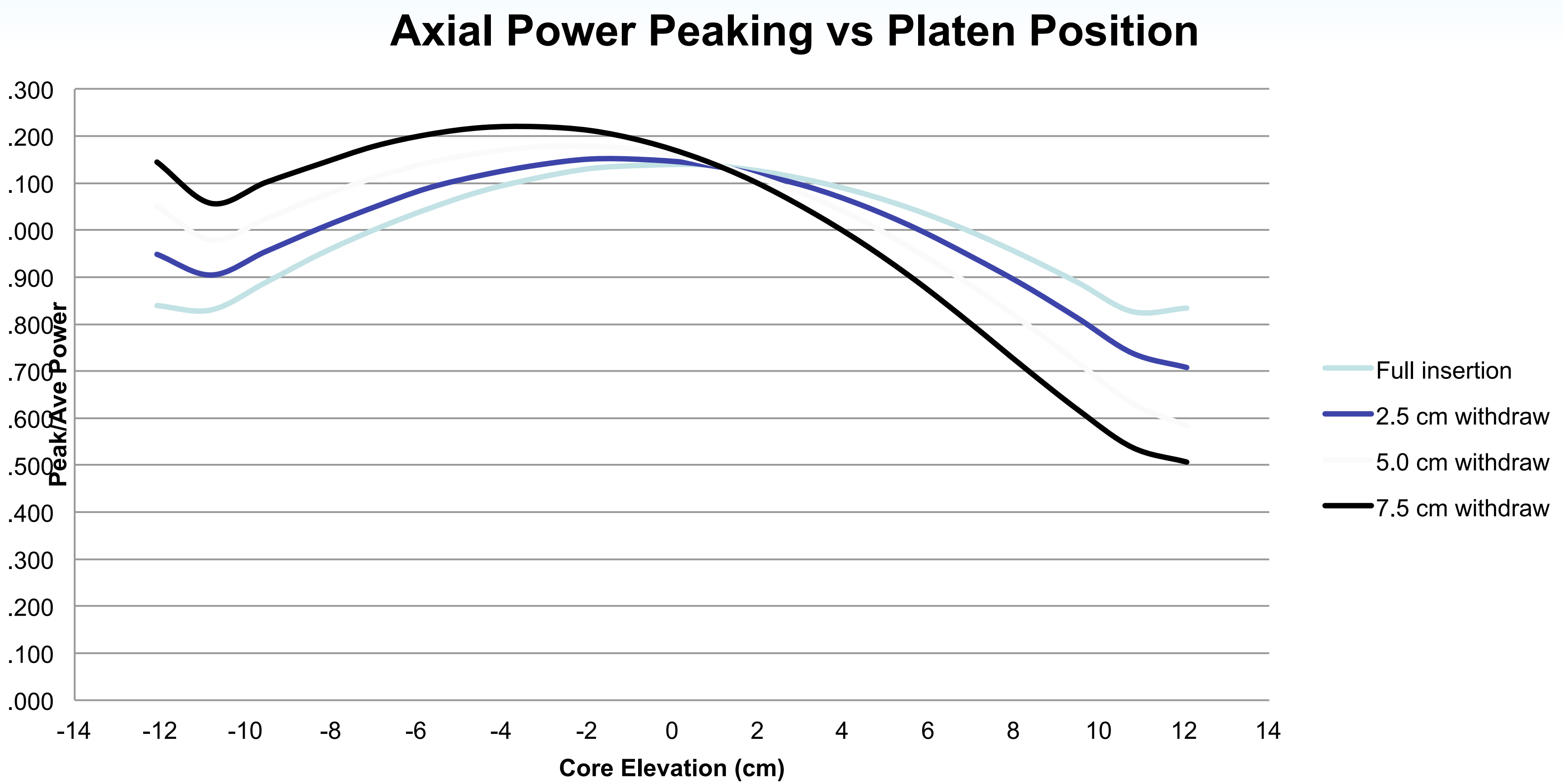
Power deposition versus table height



Power shifts downward with table – due to position radial reflector, axial reflector not as influential

Note: this is krst1f, slightly different than krst1g

Axial Power Peaking



This level of axial peaking is small compared to most reactors, despite the fact that we have an extremely large L/D. In general 10% peaking should add 10% to all temperature gradients up through the HP vapor, with a small reduction due to axial conduction through the fuel. Thus, a case run with the table withdrawn 7.5 cm would see a 10% higher delta-T than at full insertion, and at most a 10 K higher temperature in the nominal case. The other consideration is how the heat pipe performs with this non-uniform heat flux, which should be ok.

Decay Power Removal

- The nominal power density of 2 W/cc gives the fuel an adiabatic heat up rate of 0.6 K/s.
  - Rate is slightly higher at room temp (lower CP) and we could decide to let reactor power go >5 kWt for a while to speed up transient.
    - The first run of DUFF ran at about 10 kWt for the first 2 minutes, resulting in core heat up of almost 2 K/s during that time.
- After shutdown, assuming an average of 1% power over several hours, the core would heat up only ~20 K per hour (assuming it was perfectly insulated).
  - The core is well, but not perfectly insulated, and it will easily reject to ~50 W to keep it from heating up
    - And rejection will increase if temperature does go up.
  - Also, the decay power will be much lower than traditional values because of such short operation time.
- FRINK will eventually perform detailed transient calculations for KRUSTY, as well as other simplified calcs.

Topics Covered

- Reference Kilopower configuration
- Reference KRUSTY configuration
- KRUSTY Design sensitivities
- KRUSTY Reactivity Coefficients
- KRUSTY Criticality Safety and Control
- **KRUSTY Core activation/dose**
- KRUSTY Shielding, room activation/dose

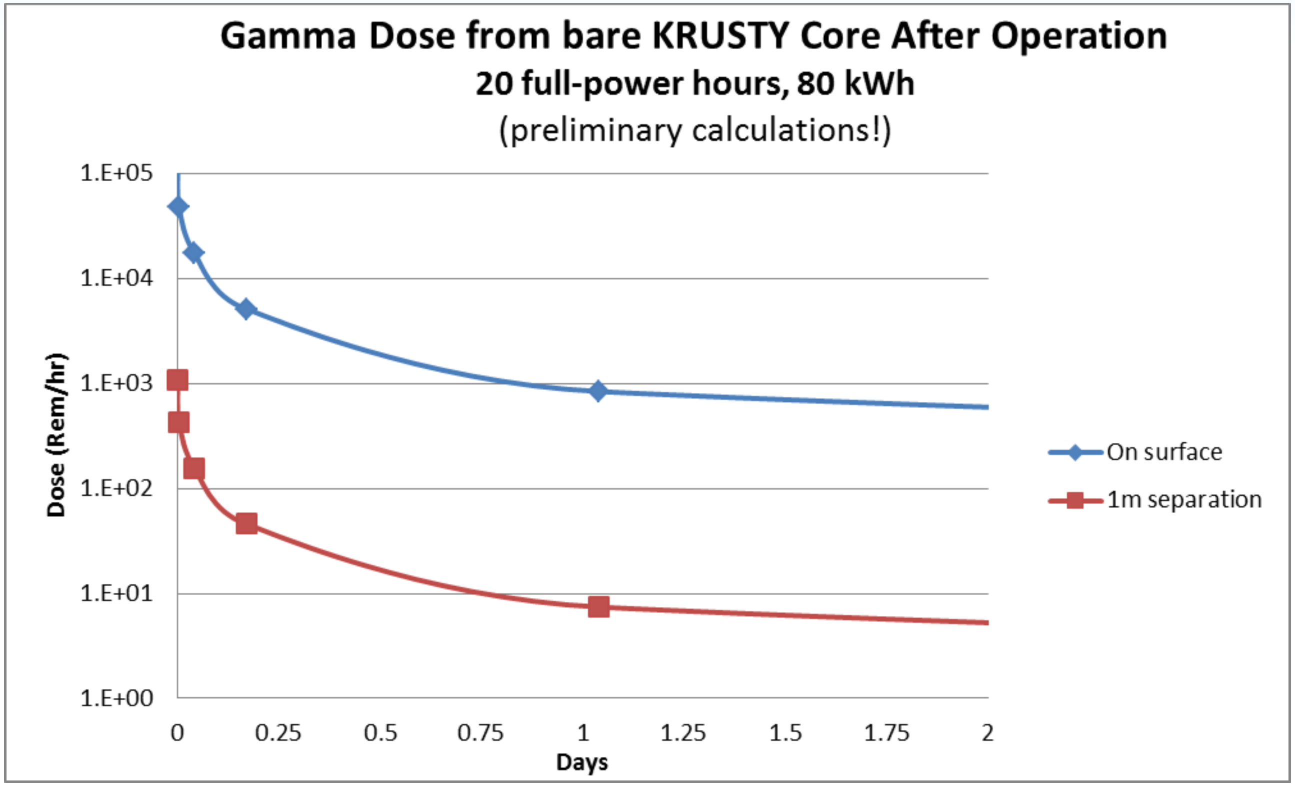
KRUSTY Core Post-Test Radioactivity

- How long will it take to handle, transport core?
- “Best case” may be we get 20 hours of full power operation, 80 kWh
- MONTEBURNS simulation of a one week intensive campaign, 4 hours each day at 4 kWt
- MAGGIE used to calculate gamma source
  - Neutron dose negligible based on past calculations, but should check again
  - Alpha source will never really change from pre-burn state
    - Plus, lack of alpha-n material makes non-factor (unless inhaled, ingested)

Core Activity Timeline

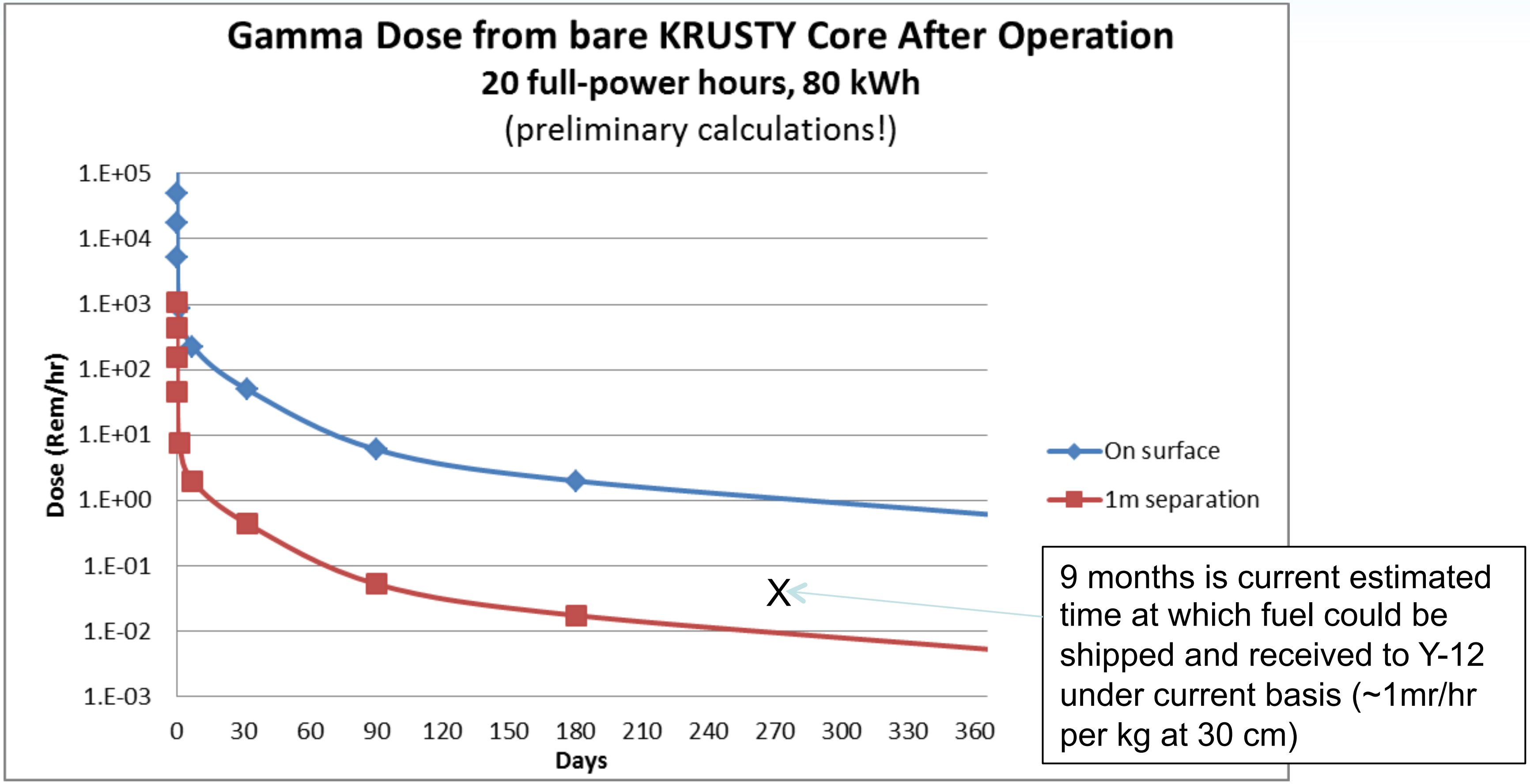
Time Step (days)	Accumulated (days)	Power (kWt)	Activity (Curies)
	0.000		1.4
0.1667	0.167	4.0	17742.3
0.8333	1.000		196.1
0.1667	1.167	4.0	17902.5
0.8333	2.000		273.7
0.1667	2.167	4.0	17972.0
0.8333	3.000		319.2
0.1667	3.167	4.0	18016.0
0.8333	4.000		351.6
0.1667	4.167	4.0	18045.6
0.0035	4.170		8655.2
0.0382	4.208		2884.3
0.1285	4.337		1032.9
0.8715	5.208		318.4
6.1285	11.337		67.8
24.309	35.646		17.0
340.941	376.587		2.0

Core Gamma Dose Rate vs Time --after final shutdown



Dose while the core is within the assembly will be lower. Plan on calculating dose standing next to Comet once configuration is known. Would be advantage to having the shield hang from top (so it still surrounds core after operation), or don't hang the core below top plate.

Gamma Dose Rate vs Time



Most of the dose after 30 days is from gammas of energy <1 MeV, which are effectively shielding by thin layer of high-Z material.

KRUSTY Actinide Inventory

Fresh

	density	activity
	atom/b-cm	curies
U 235	3.69E-02	6.17E-02
U 238	2.46E-03	6.46E-04
U 234	2.82E-04	1.35E+00

Of course our initial fuel will not be this clean.

Burned KRUSTY fuel is still cleaner than pre-burned SP-100 fuel in terms of actinide levels (up to 10 ppm Pu)

3 micro grams of fuel burned
0.00001 % burnup

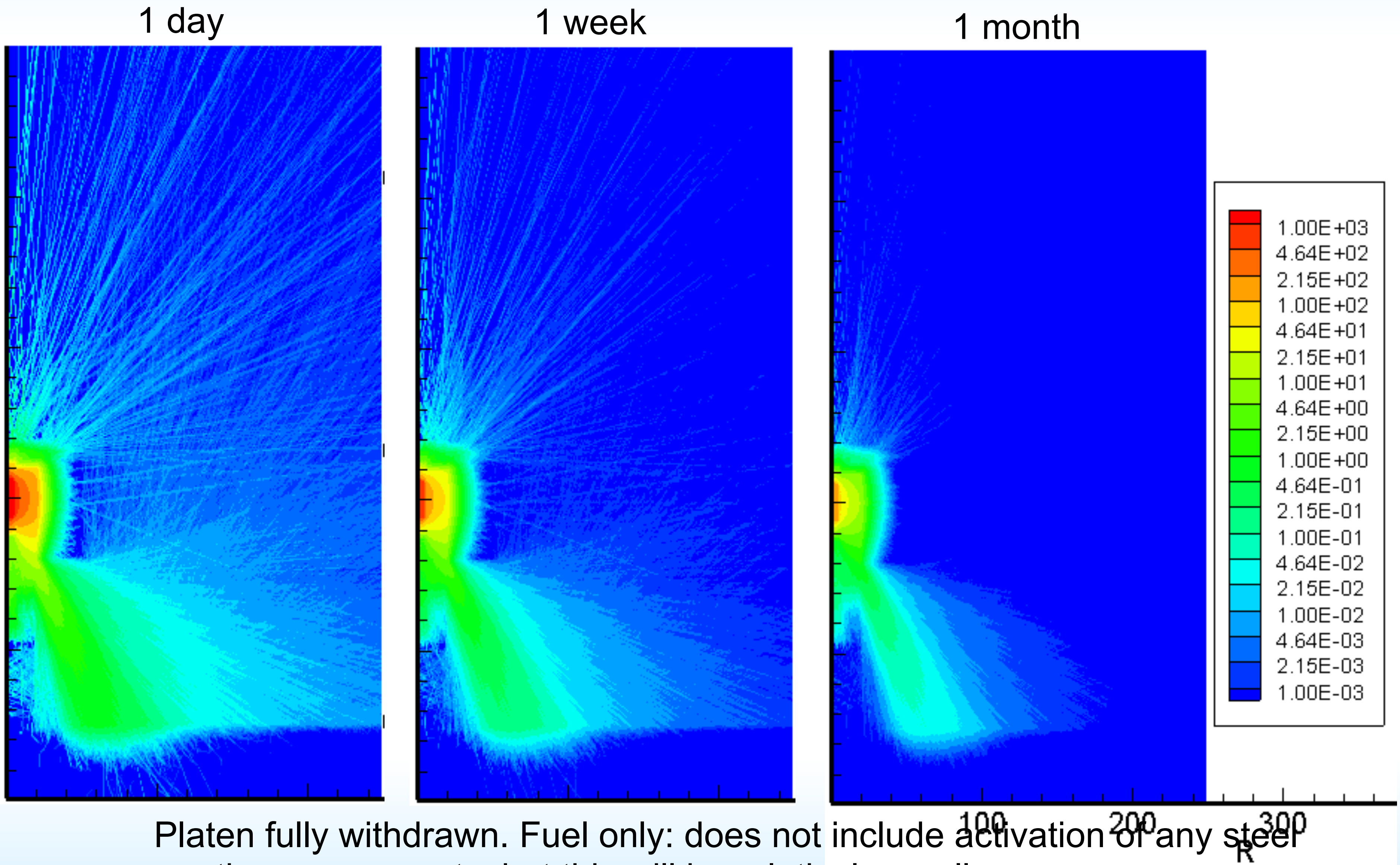
1 day after 80 kWhr

	density	activity
	atom/b-cm	curies
U 235	3.69E-02	6.17E-02
U 238	2.46E-03	6.46E-04
U 234	2.82E-04	1.35E+00
U 236	8.53E-10	4.28E-08
Pu239	2.15E-11	1.05E-06
Np239	1.67E-11	3.05E+00
Th230	1.13E-11	1.77E-07
U 237	1.07E-12	6.81E-02
Np237	3.90E-13	2.14E-10
Pa231	3.67E-13	1.32E-08
Th231	1.48E-13	5.96E-02
U 233	3.65E-14	2.70E-10
Th234	5.05E-15	8.99E-05
Th232	8.47E-16	7.09E-17
Pa233	9.44E-17	1.50E-06
U 232	1.68E-17	2.82E-10
Pa234	8.47E-18	1.30E-05
Pu240	1.19E-18	2.13E-13
Pa234*	1.70E-19	8.99E-05
Pa232	1.46E-19	4.80E-08
Np238	5.77E-21	1.17E-09
Pu238	5.61E-21	7.52E-14

1 yr after 80 kWhr

	density	activity
	atom/b-cm	curies
U 235	3.69E-02	6.17E-02
U 238	2.46E-03	6.46E-04
U 234	2.82E-04	1.35E+00
U 236	8.53E-10	4.28E-08
Th230	8.20E-10	1.28E-05
Pu239	3.82E-11	1.86E-06
Pa231	3.74E-11	1.34E-06
Np237	1.46E-12	8.02E-10
Th231	1.53E-13	6.17E-02
U 233	3.66E-14	2.70E-10
Th234	3.63E-14	6.46E-04
Th232	8.73E-16	7.30E-17
U 232	1.67E-17	2.82E-10
Pa234*	1.22E-18	6.46E-04
Pu240	1.19E-18	2.13E-13
Pa234	5.46E-19	8.40E-07
Pa233	5.73E-20	9.11E-10
Pu238	1.13E-20	1.51E-13

KRUSTY Dose After Campaign



Platen fully withdrawn. Fuel only: does not include activation of any steel or other components, but this will be relatively small.

Topics Covered

- Reference Kilopower configuration
- Reference KRUSTY configuration
- KRUSTY Design sensitivities
- KRUSTY Reactivity Coefficients
- KRUSTY Criticality safety and control
- KRUSTY Core activation/dose
- **KRUSTY Shielding, room activation/dose**

KRUSTY Shielding

- Ideal goal is to keep room activation for a KRUSTY run in the same ballpark as a DUFF run.
- DUFF runs were rather short.
  - DUFF Test#1 operated 1.3 kWh
  - DUFF Test#2 operated 2.0 kWh
    - Flattop Free Runs ~1 kWh
- For a KRUSTY run we are hoping to run near full power (4 or 5 kWt) for several hours
  - KRUSTY run up to ~20 kWh per run?
    - Thus if we're lucky 10 times more energy than a DUFF run.

KRUSTY Shielding

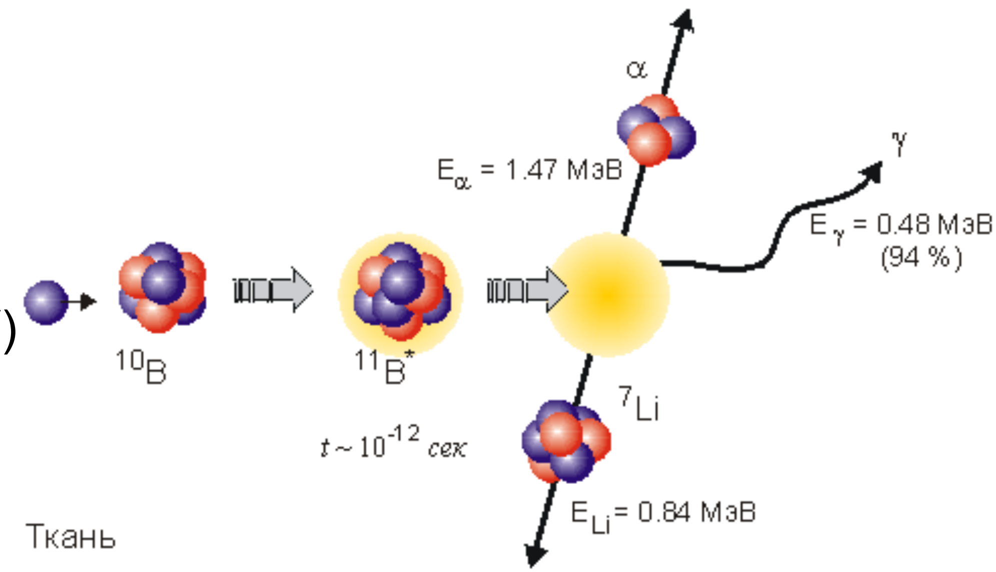
- How well should we shield DUFF to prevent room activation?
  - We could try to shield KRUSTY so that leaking neutron fluxes are 10 times lower than DUFF.
    - Thus 1 KRUSTY run would produce the same room activation as 1 DUFF run, but this proved very difficult.
  - Note that “room activation” is not the limiter of room re-entry; rather, it is the activation of the nuclear assembly itself.
    - The shielding of the room from the activated experiment is done extremely well by the shield (with the only exception being below the core; i.e. the manhole cover issue)
  - The reason to prevent room activation is the potential to create background radioactive noise for sensitive experiments.
- Given the above, a goal was selected to keep the neutron leakage rate from KRUSTY 4x lower than for DUFF (when operating at the same power).
  - Therefore, if we’re lucky enough to complete a 5 hour 4-kWt KRUSTY run, it will activate the room 2 or 3 times more than a DUFF run, which should be acceptable.
    - Assuming that previous DUFF and Flaptop free runs did not pose a significant room activation issue, or at least the room activation was deemed acceptable.

Model Notes

- Floor put into model, but not walls or ceiling.
  - Floor assumed 1 foot of Portland Concrete with 25 w/o rebar.
- No aspect of Comet or balance of KRUSTY beyond the shielding is modeled (other than Comet platen and upper table, and KRUSTY vacuum chamber.
  - Anything else would have insignificant worth considering how well KRUSTY is reflector/shielded.
- The configuration for all of the following calculations is krst1g

Need to reduce capture gammas.

- Neutrons can penetrate far into the shield and then create a high energy gamma when captured by metal (up to ~8MeV).
- Boron capture is best option
  - Super high cross section
  - Benign result
    - Non radioactive daughters
    - Low energy gamma (.48 MeV)



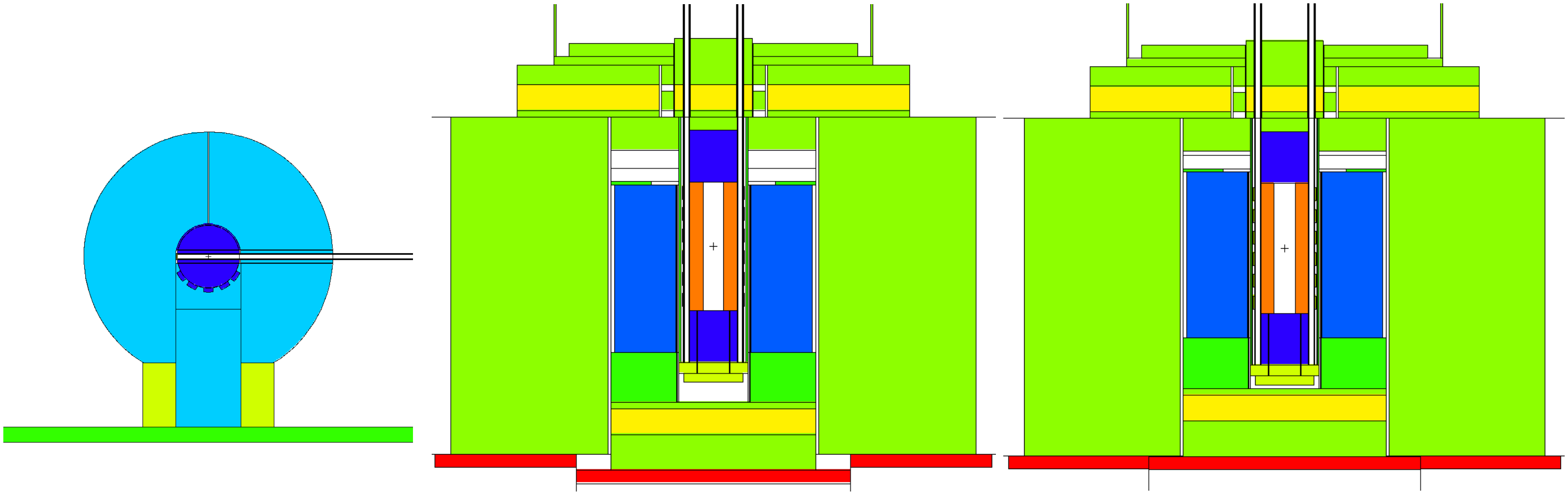
- Options
  - B4C
  - Borated steel
  - Borobond
  - Borated poly
- Best if use a high-boron density material followed by high Z outer layer (for the .48 MeV gammas), but steel still works well.

Arriving at Current Solution

- First model used 8” SS
  - Did not cut it, really bad on gammas (capture gammas from iron, etc.)
- Next model used 1 w/o borated SS
  - Eureka! This worked great! Unfortunately, despite online claims, MSFC found that nobody really makes this stuff, and it would be a high-cost specialty item.
- Other options such as borobond, borated-poly considered, but there were potential temperature concerns, heat up rate to >100 C might occur.
- Next model used 1” SS, 2” B4C and 4” SS
  - Again this worked neutronically, but making the cylindrical annulus from B4C would not be easy and would be costly.
- Decision to consider go all steel, but very thick
  - Cheaper carbon steel considered, but even 12” did not provide enough shielding.
- Go back to SS316, 12” thick
  - Worked neutronically, but we did not have enough axial clearance to fit it all in.
- Keep 12” radially, but go back to 1”, 2” B4C, 4’ SS axially
  - B4C thin puck-like shapes not too difficult.
- This works pretty well, but there was a lot of design iterations along the way, because of the major impact that the shield has on criticality.

System Configurations

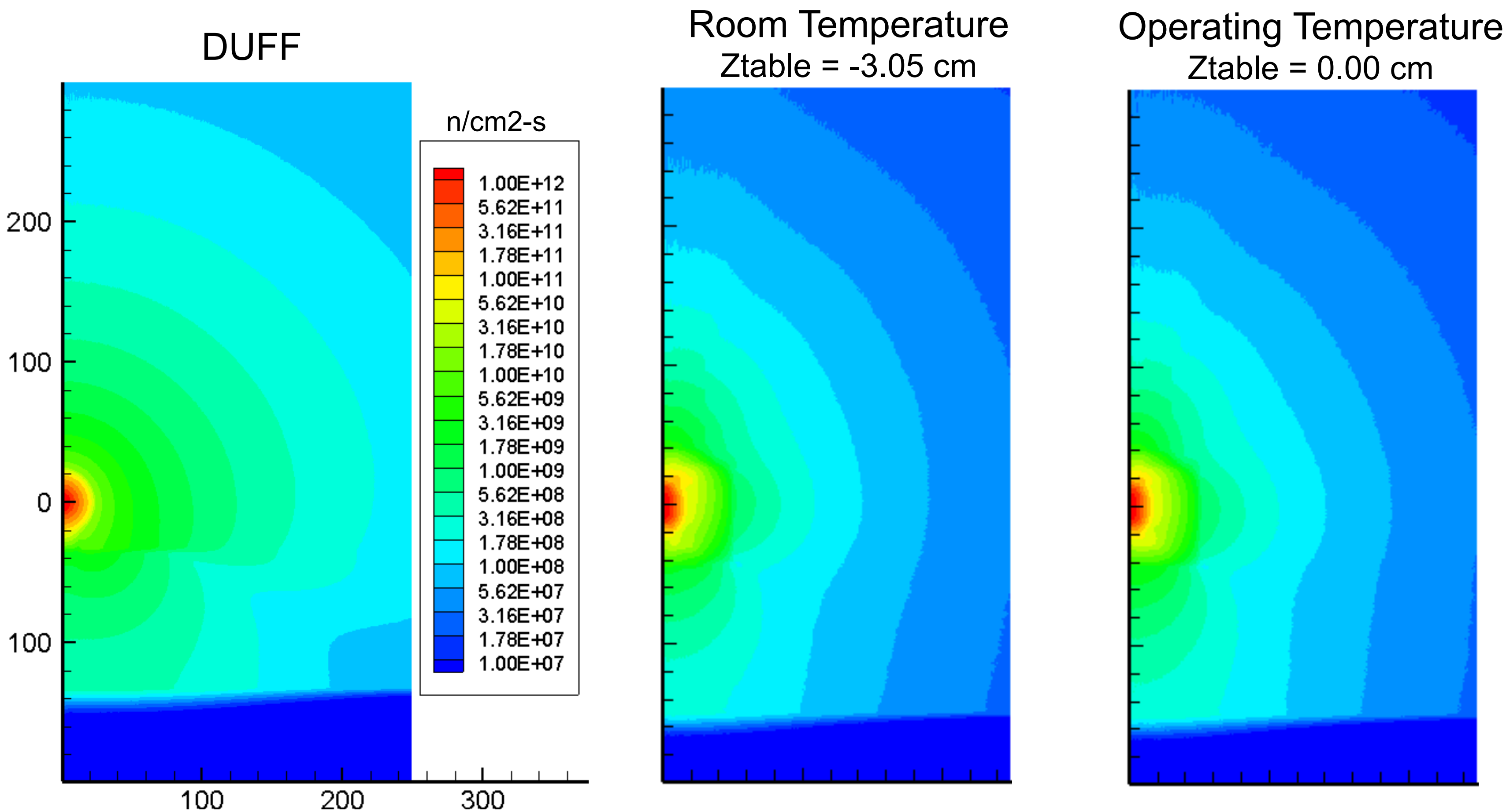
DUFF	Nominal KRUSTY Room Temperature Short-stack = 2.54 cm Ztable = -3.05 cm	Nominal KRUSTY Operating Temperature Short-stack = 2.54 cm Ztable = 0.00 cm



Approximately to scale: Flattop reflector OD is 48 cm, KRUSTY radial OD is 38 cm

DUFF vs KRUSTY: Neutron Flux >100 keV

4 kWt, Nominal Model, BeO short-stack = 2.54 cm

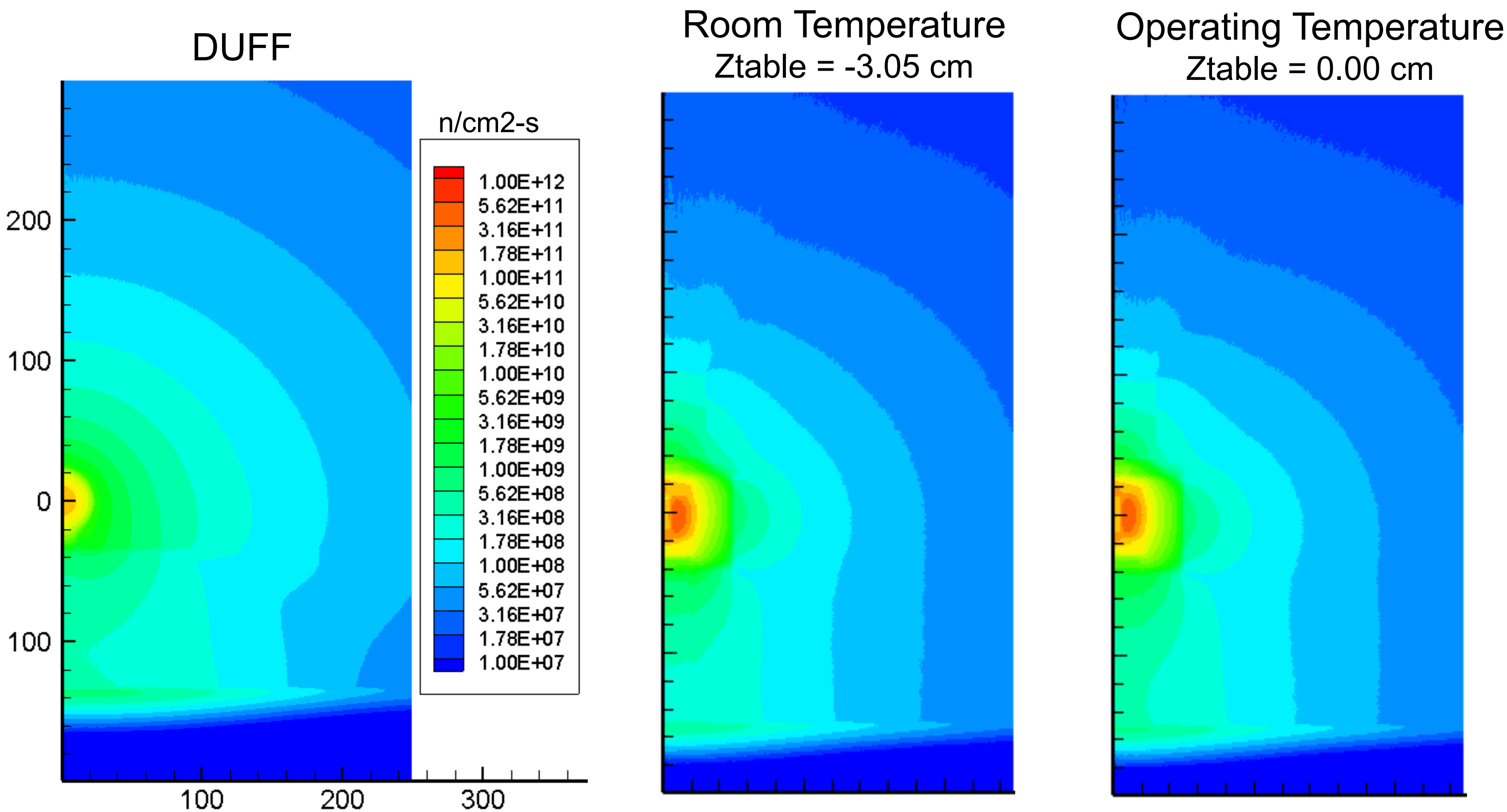


The room fast neutron flux from KRUSTY is ~4x lower than DUFF (goal achieved!); slightly more then 4x radially, and slightly less than 4x above and below.

The flux above the reactor is ~10% higher when the system is operating cold, because the BeO stack is not filling the gap in the upper corners.

DUFF vs KRUSTY: Neutron Flux <100 keV

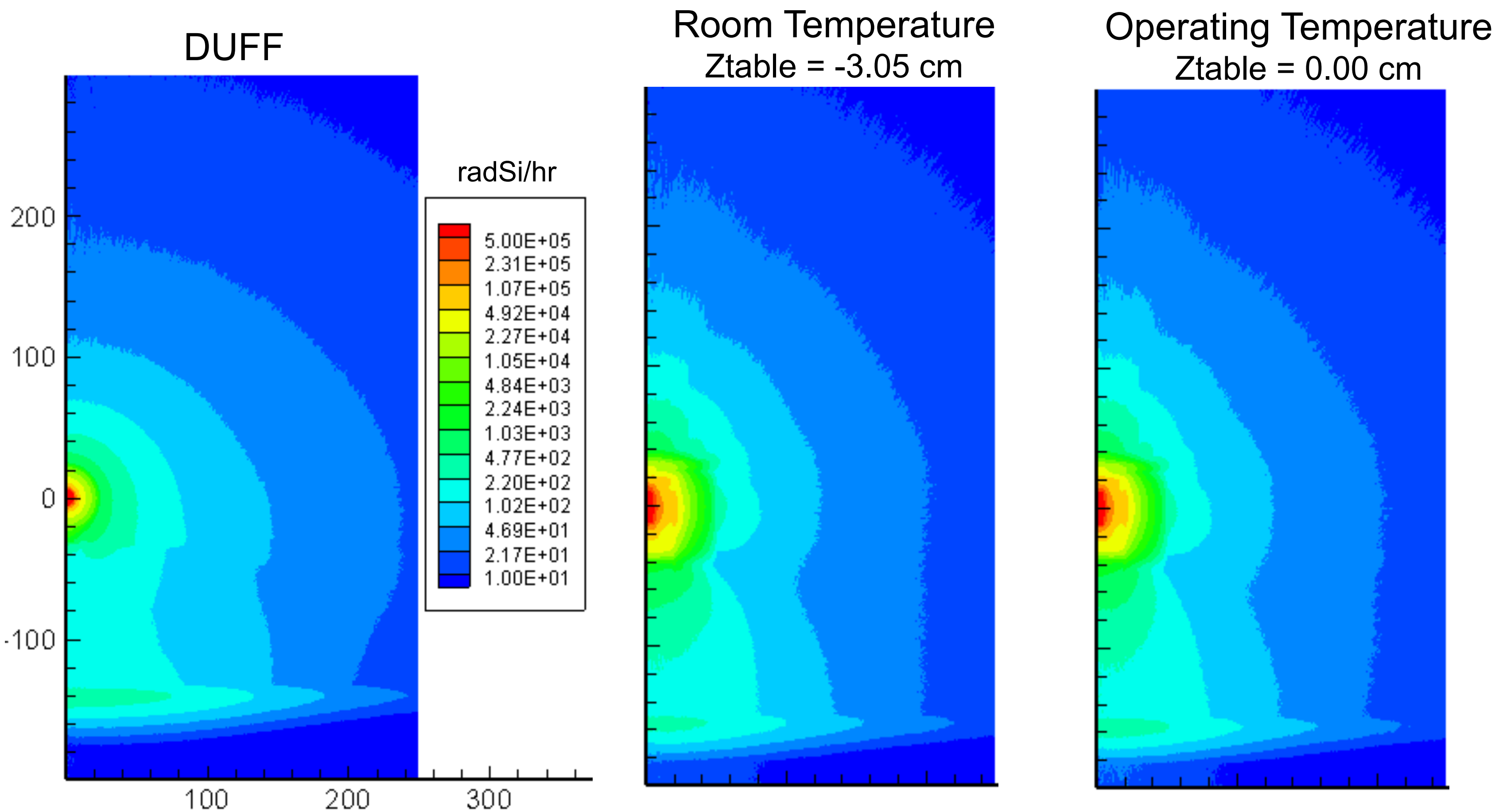
4 kWt, Nominal Model, BeO short-stack = 2.54 cm



The moderated flux of KRUSTY is ~2x lower than DUFF, but does not need to be reduced as much because the magnitude is much lower than the fast flux (each neutron type will likely cause activation regardless).
There is no B4C in the vessel flange region, thus the spike – could add B4C collar.

DUFF vs KRUSTY : Gamma Dose Rate (Rad-Si/hr)

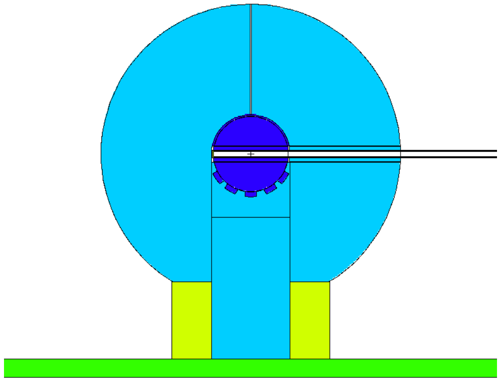
4 kWt, Nominal Model, BeO short-stack = 2.54 cm



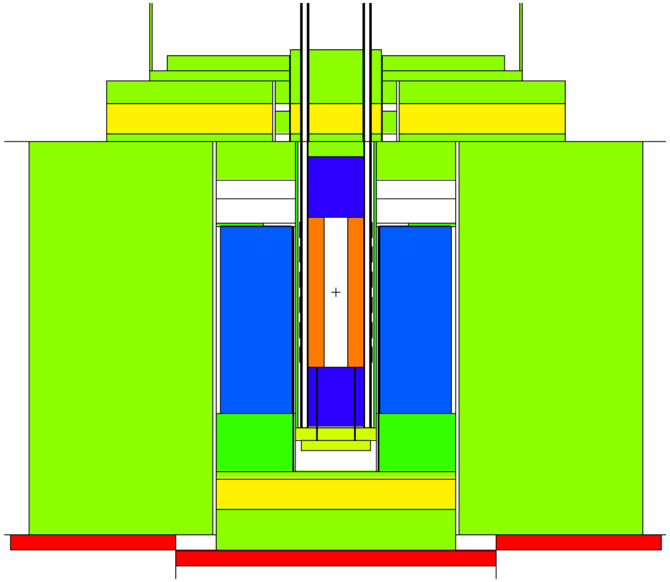
The gamma dose rate slightly lower than DUFF in the radial direction and below, and higher above the reactor. Additional shielding and/or the B4C collar could help if desired, but integral gamma dose should not be an issue regardless.

System Configurations

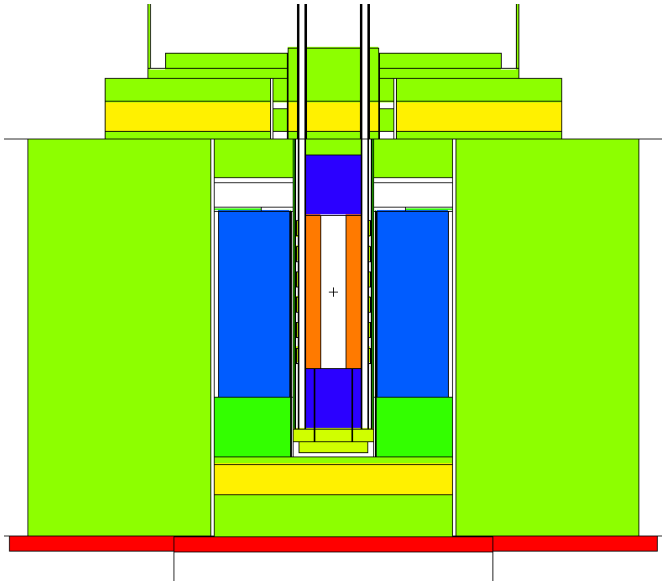
DUFF



Over-Juiced KRUSTY
Room Temperature
Short-stack = 4.03 cm
Ztable = -2.61 cm



Over-Juiced KRUSTY
Operating Temperature
Short-stack = 4.03 cm
Ztable = 2.61 cm

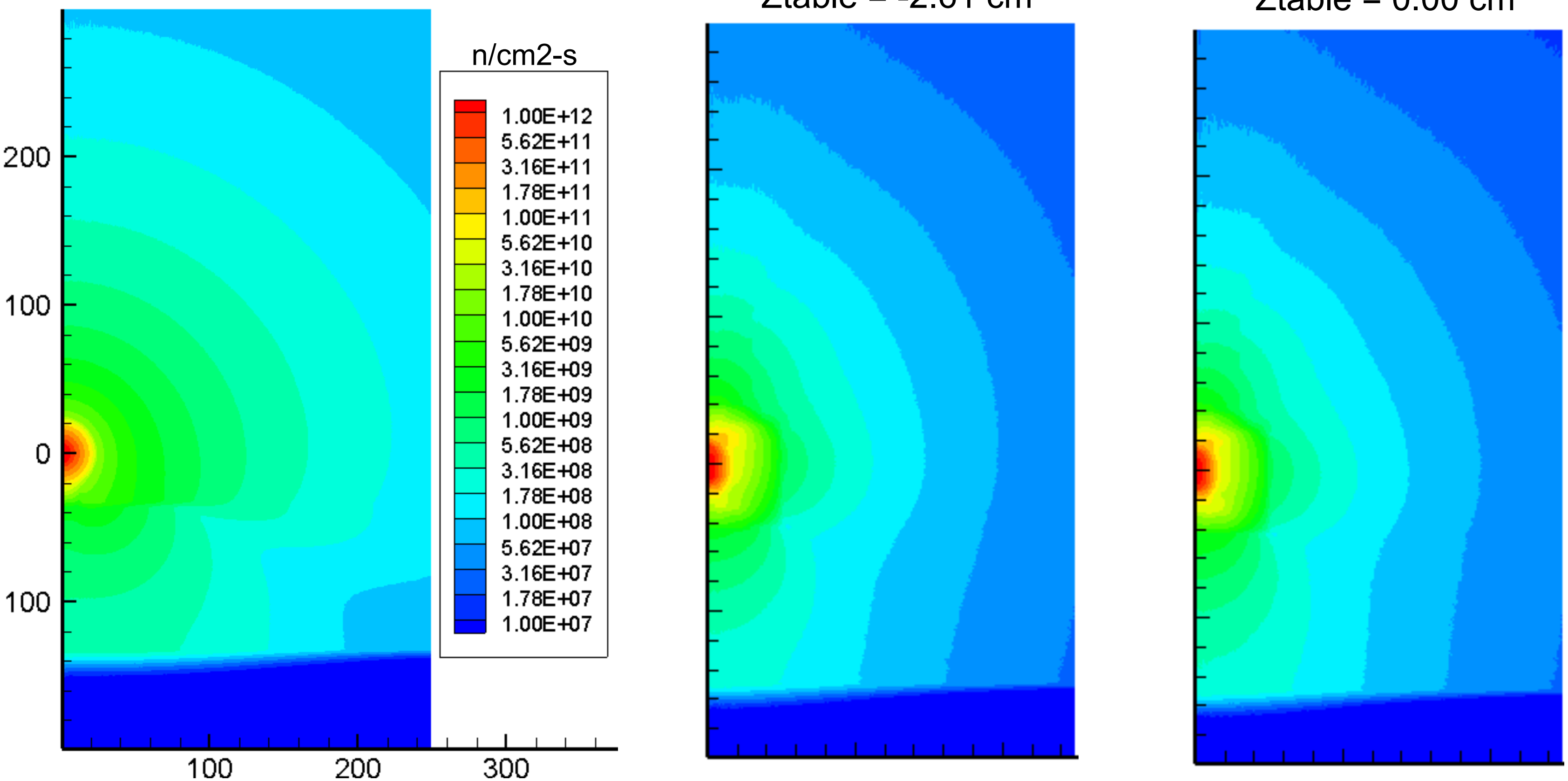


Approximately to scale: Flattop reflector OD is 48 cm, KRUSTY radial OD is 38 cm

DUFF vs KRUSTY: Neutron Flux >100 keV

<u>4 kWt, Over-Juiced Model, BeO short-stack = 4.03 cm</u>

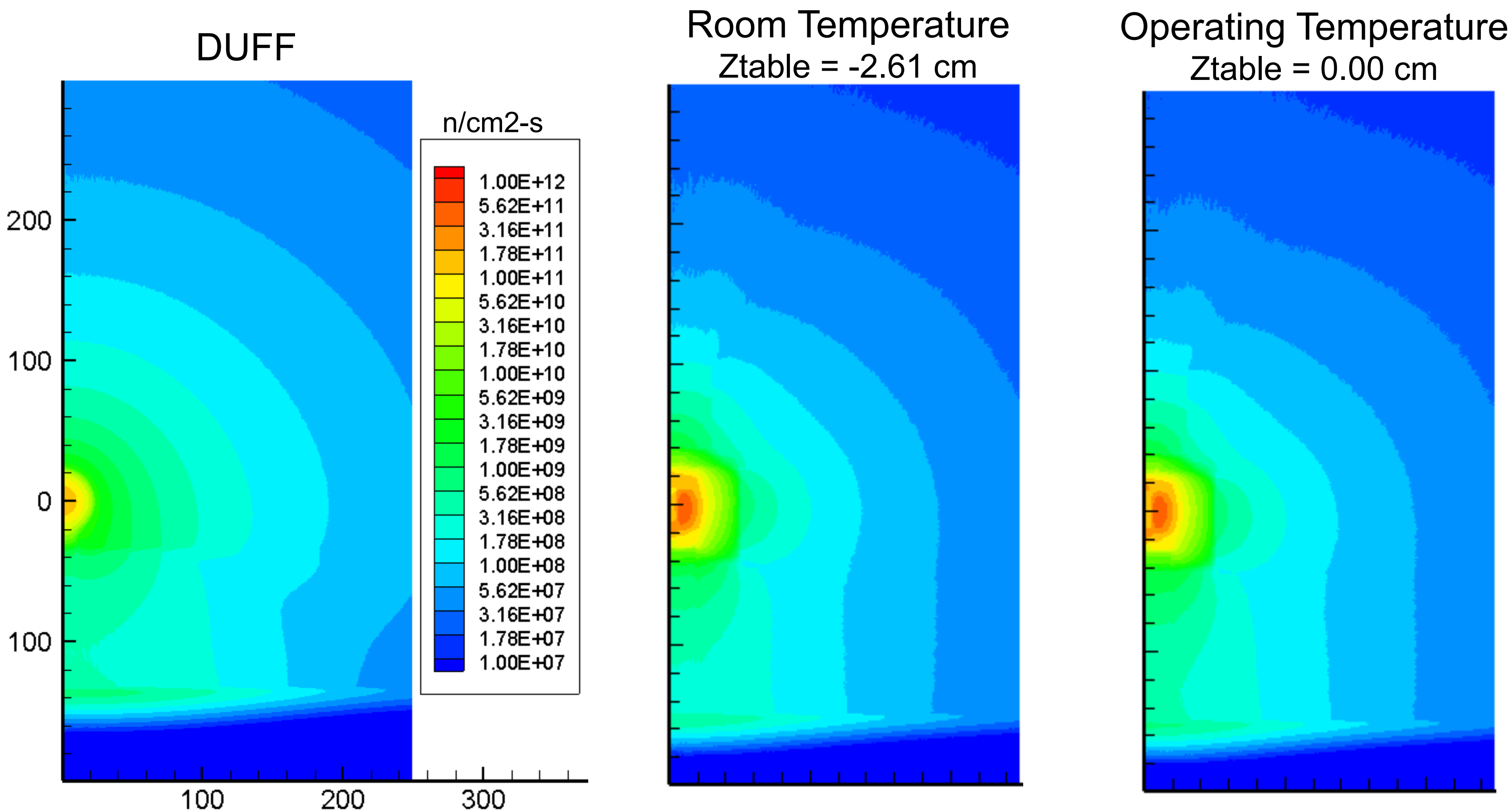
DUFF | Room Temperature, Ztable = -2.61 cm | Operating Temperature, Ztable = 0.00 cm



Shielding is still good, ~4x better than DUFF, even with the shorter stack of BeO in this scenario (6.64 cm from full-stack, thus 1.64 cm of fuel is exposed at room temperature criticality).

DUFF vs KRUSTY: Neutron Flux <100 keV

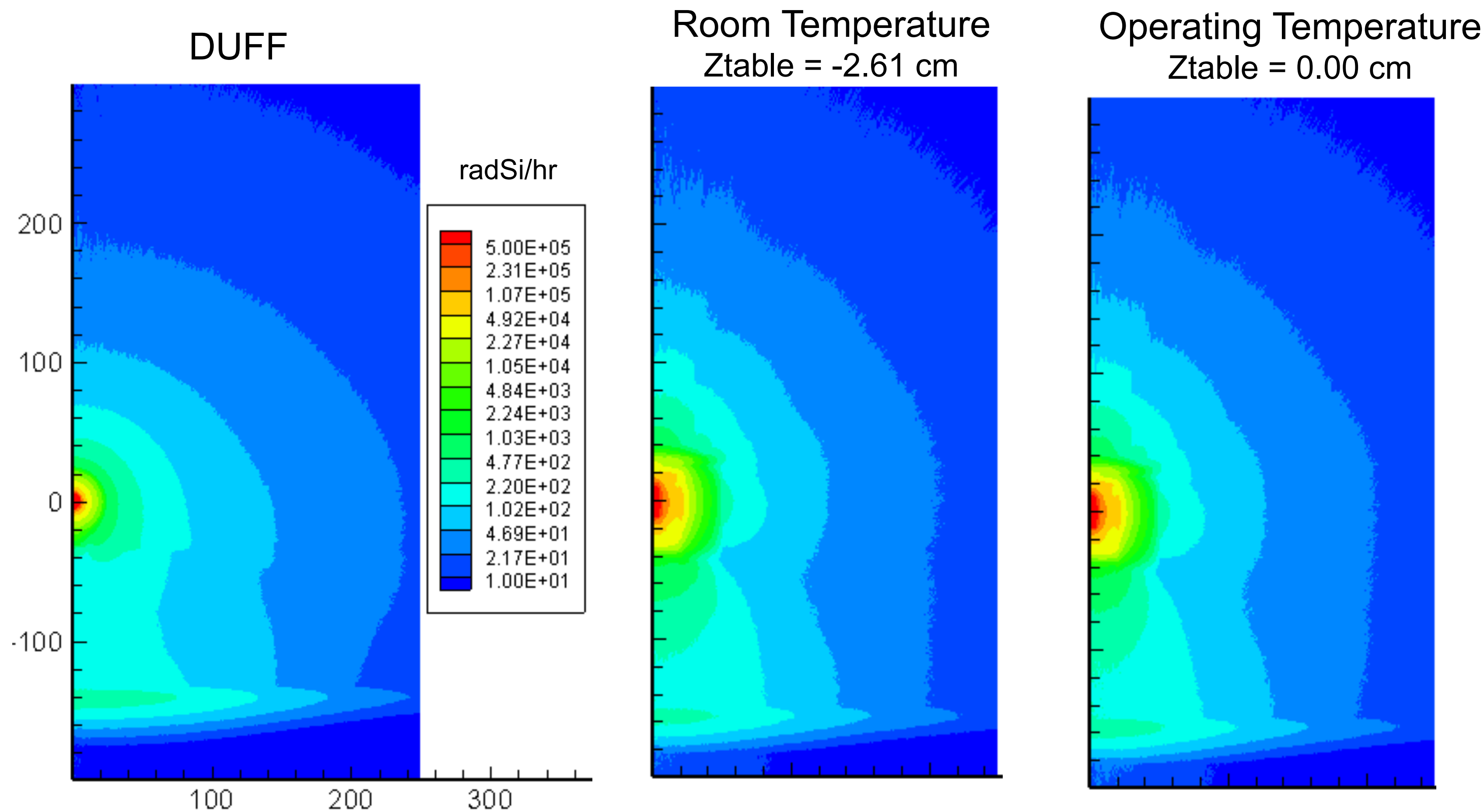
4 kWt, Over-Juiced Model, BeO short-stack = 4.03 cm



Still looks good. Again, should investigate B4C collar above flange.

DUFF vs KRUSTY : Gamma Dose Rate (Rad-Si/hr)

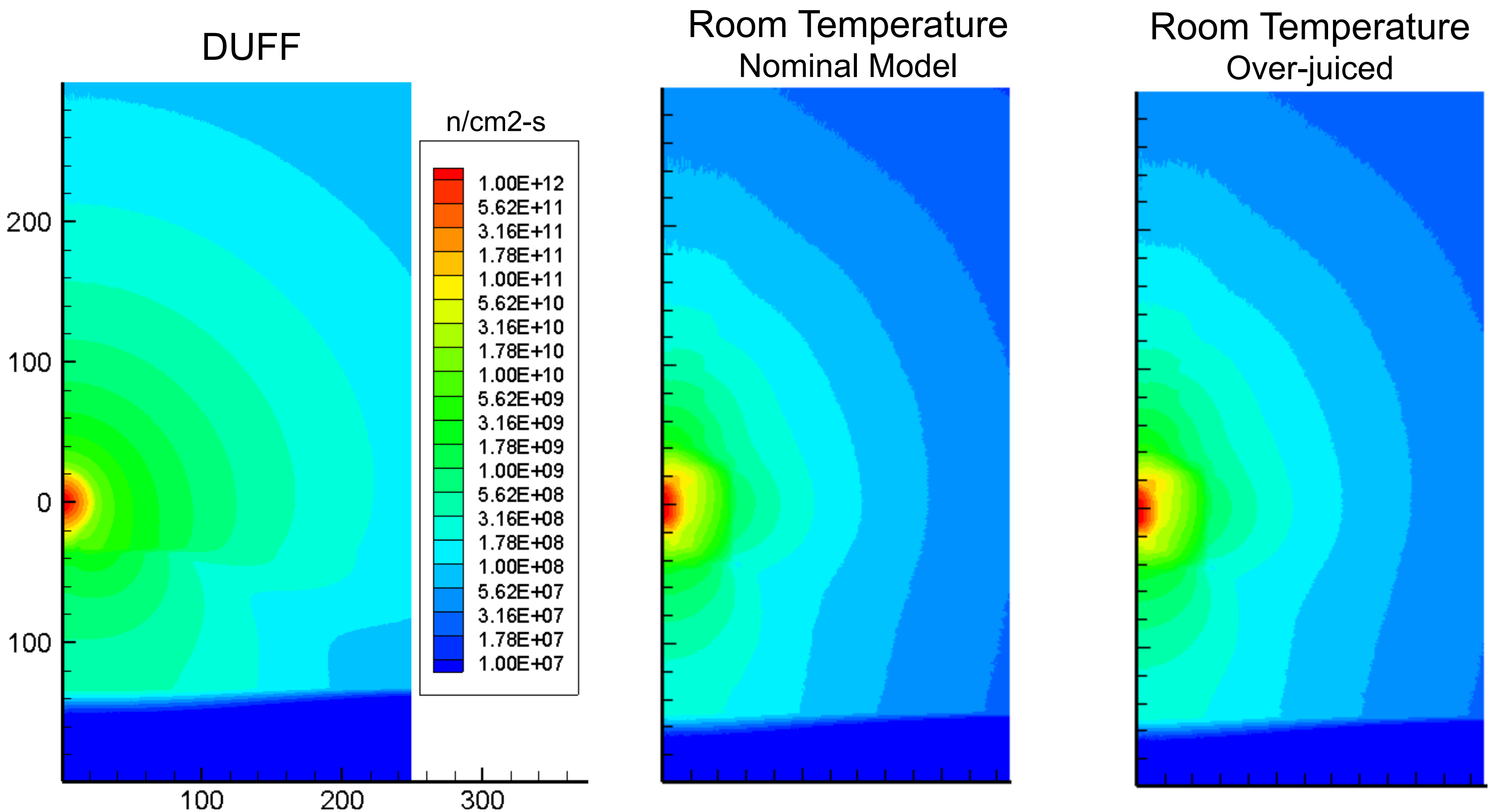
4 kWt, Over-Juiced Model, BeO short-stack = 4.03 cm



Similar to nominal scenario.

DUFF vs KRUSTY: Neutron Flux >100 keV

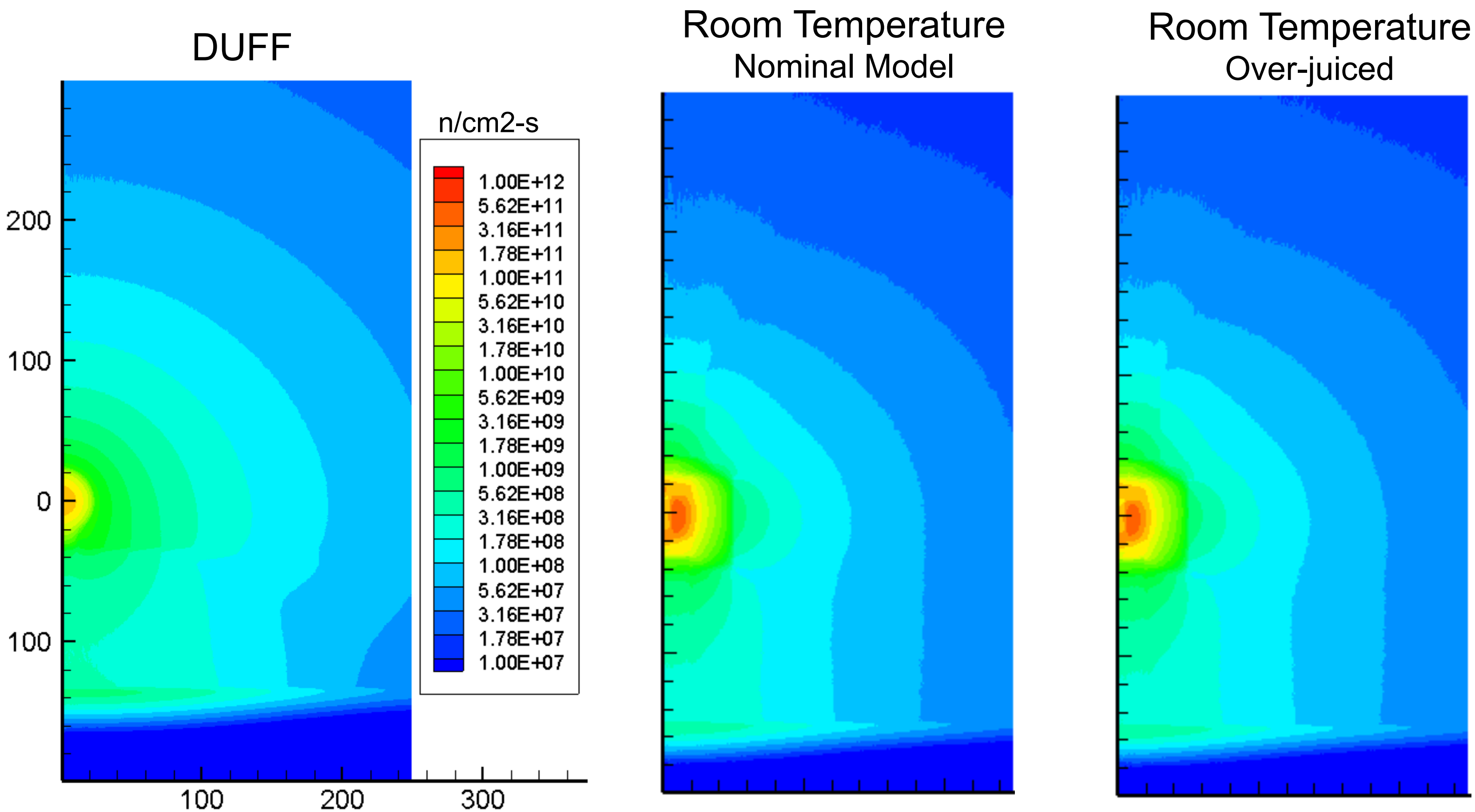
4 kWt, Nominal Model vs Over-juiced at Room temp (table lowered)



More of the fuel/core is uncovered in the over-juiced scenario (1.64 cm vs 0.59 cm in the nominal scenario), but this only causes a modest increase (~10%?) in room neutron flux

DUFF vs KRUSTY: Neutron Flux <100 keV

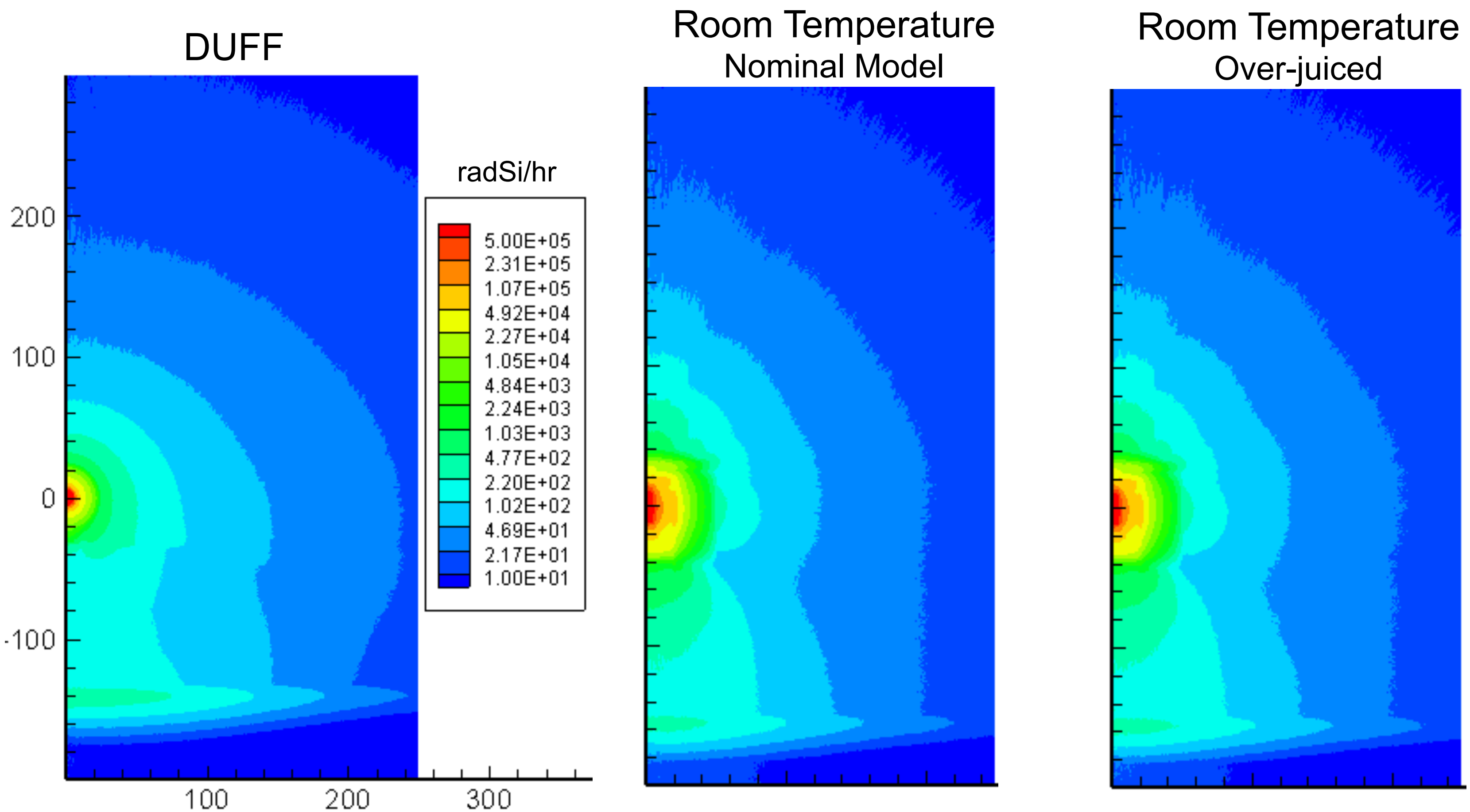
4 kWt, Nominal Model vs Over-juiced at Room temp (table lowered)



Small difference (<5% increase), despite 1cm more of fuel exposed in over-juiced case.

DUFF vs KRUSTY : Gamma Dose Rate (Rad-Si/hr)

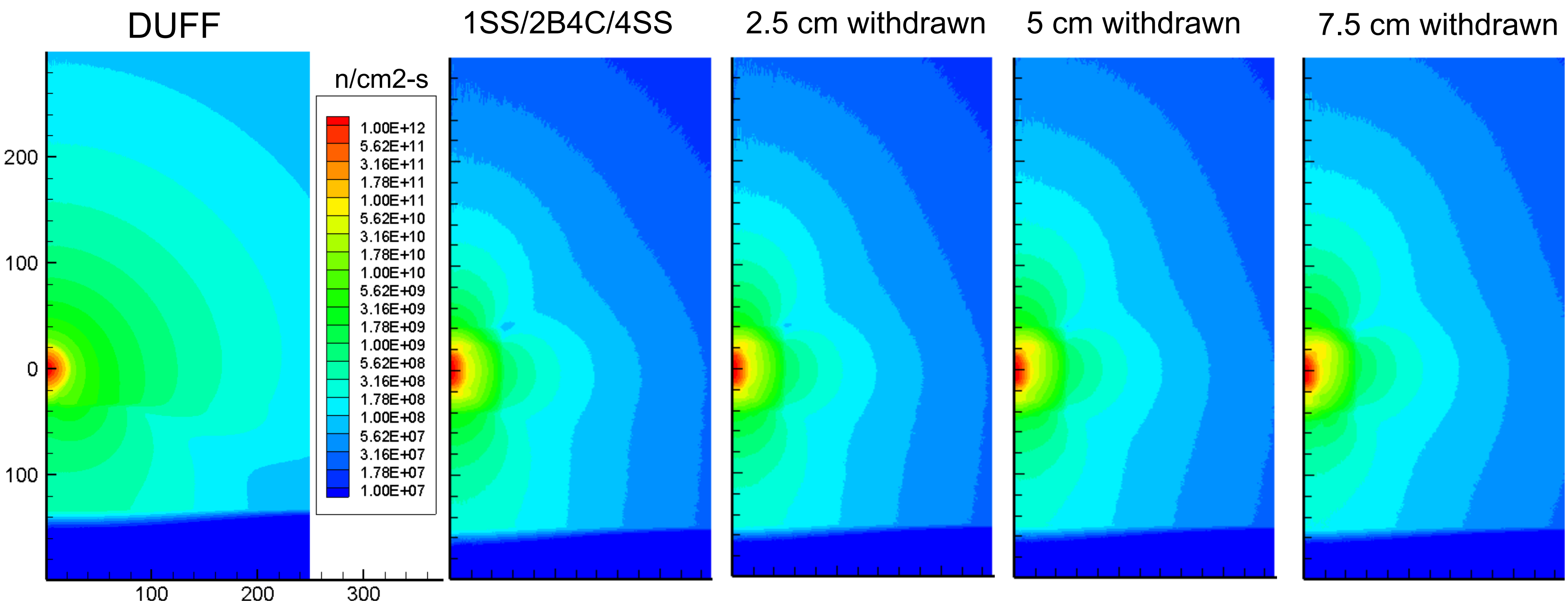
4 kWt, Nominal Model vs Over-juiced at Room temp (table lowered)



Only about a ~5% increase in room gamma dose results from the 1cm more of fuel exposed in the over-juiced case.

DUFF vs KRUSTY: Neutron Flux >100 keV

4 kWt, Older, Less Detailed Model vs platen position

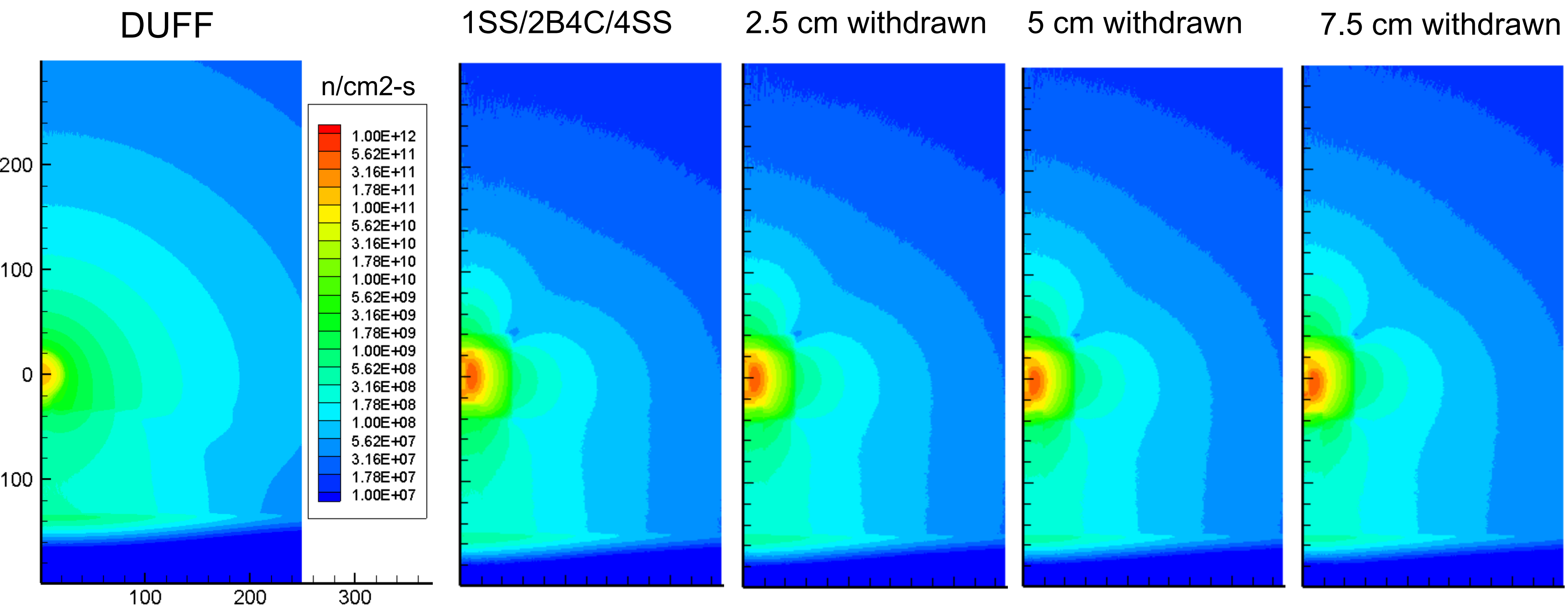


This shows that the shielding still pretty good even if system would go critical with platen withdrawn 3” (which is a non-physical condition).

Note withdrawn cases are 1 to 2% lower that they should be relative to fully inserted because of drop in keff multiplication.

DUFF vs KRUSTY: Neutron Flux <100 keV

4 kWt, Older, Less Detailed Model vs platen position



This shows that the shielding still pretty good even if system would go critical with platen withdrawn 3” (which is a non-physical condition).

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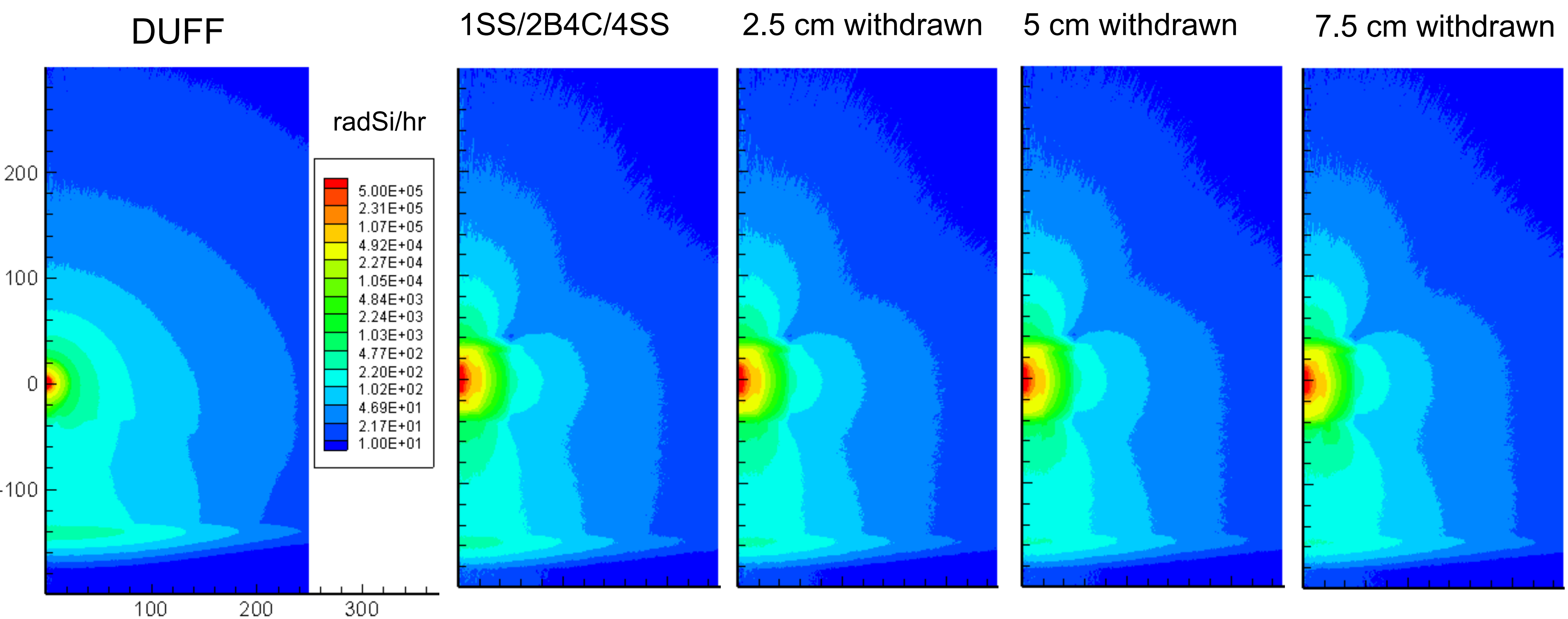
DUFF vs KRUSTY : Gamma Dose Rate (Rad-Si/hr)

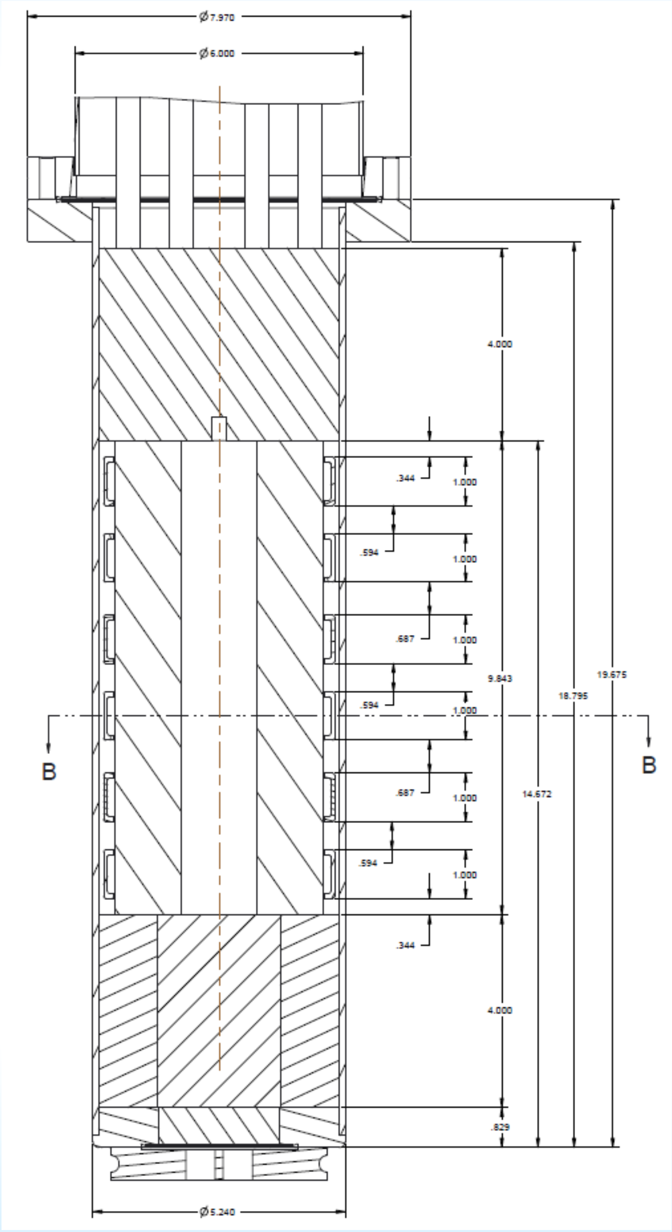
4 kWt, Older, Less Detailed Model vs platen position



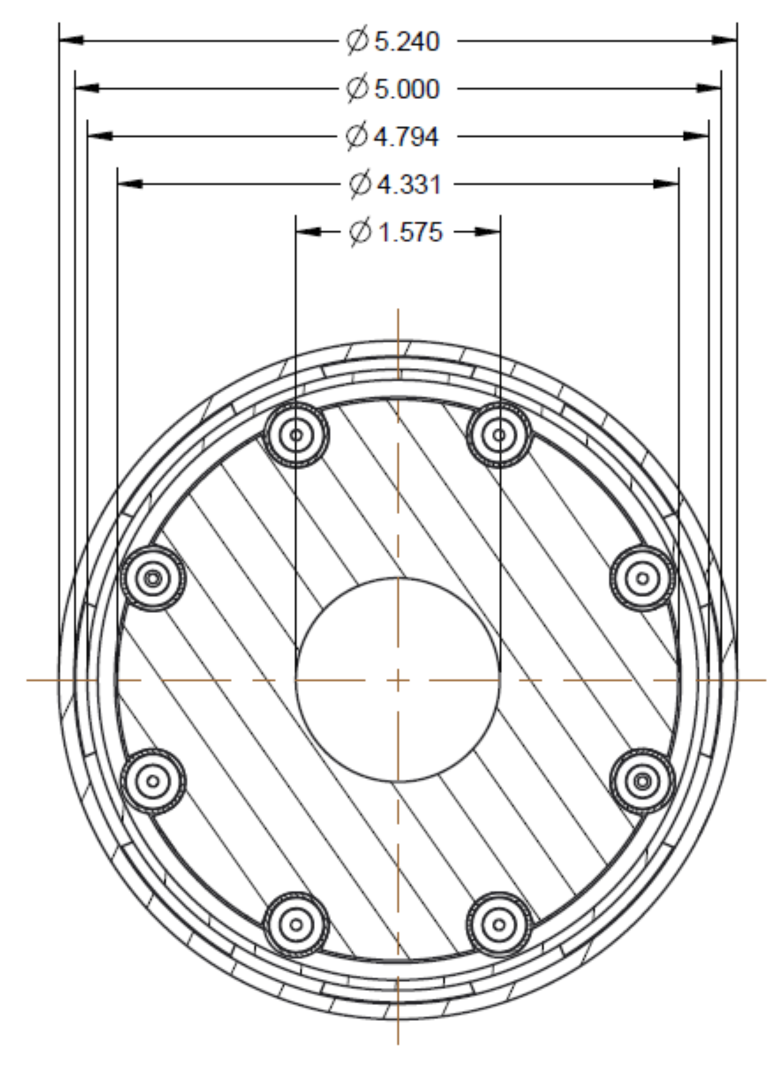
This shows that the shielding still pretty good even if system would go critical with platen withdrawn 3” (which is a non-physical condition).

Note withdrawn cases are 1 to 2% lower that they should be relative to fully inserted because of drop in keff multiplication.

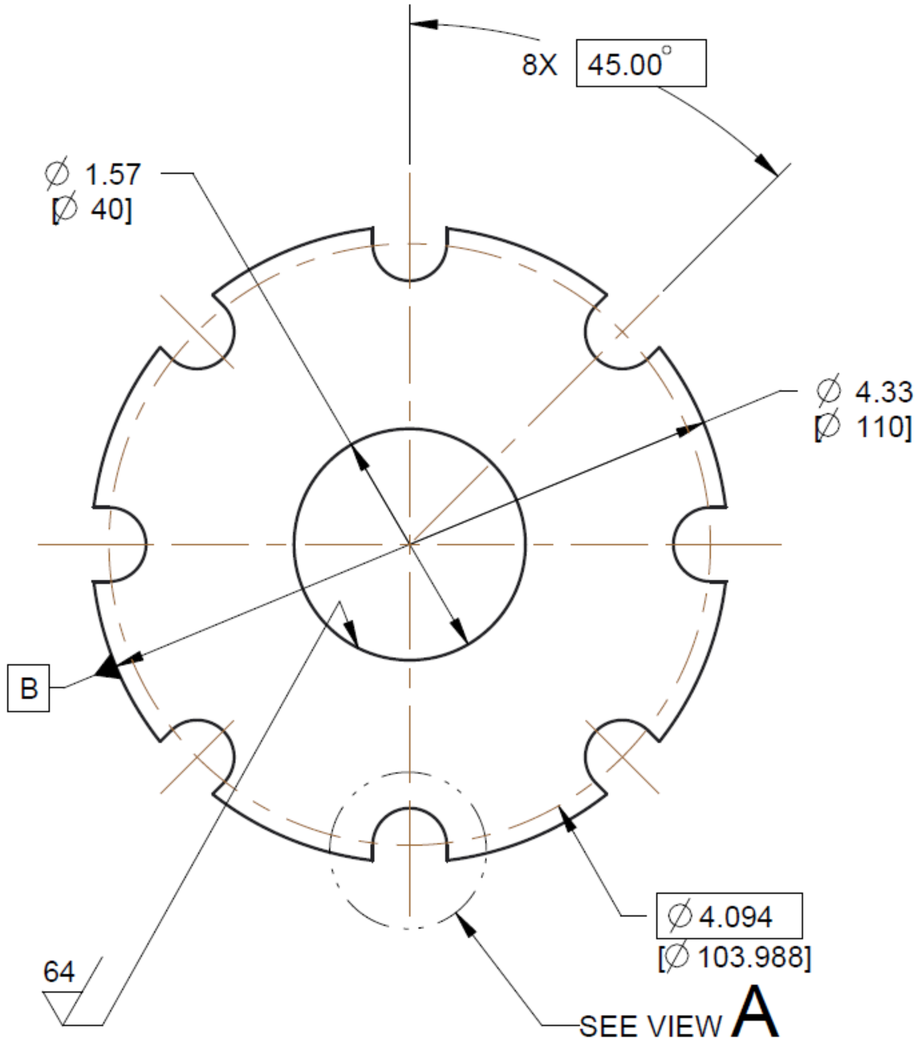
Backup



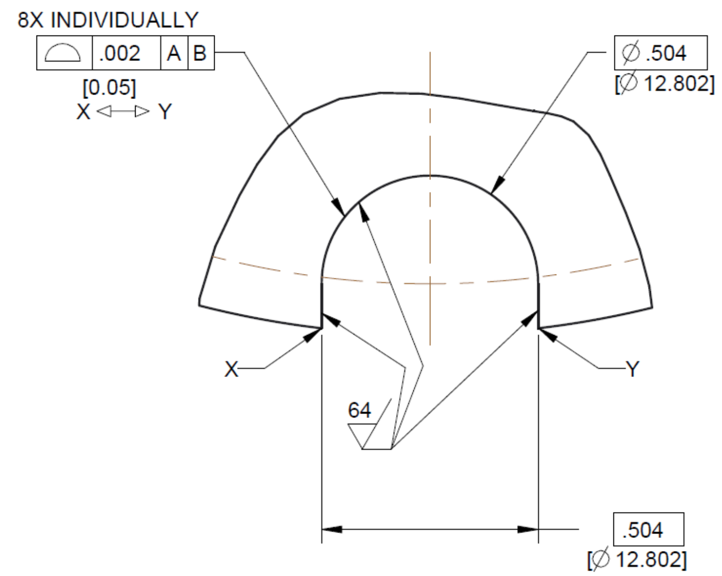
Ø7.970
Ø6.000
4.000
.344
1.000
.594
1.000
.687
1.000
.594
1.000
.687
1.000
.594
1.000
.344
4.000
.829
9.843
14.672
18.795
19.675
B
B
Ø5.240



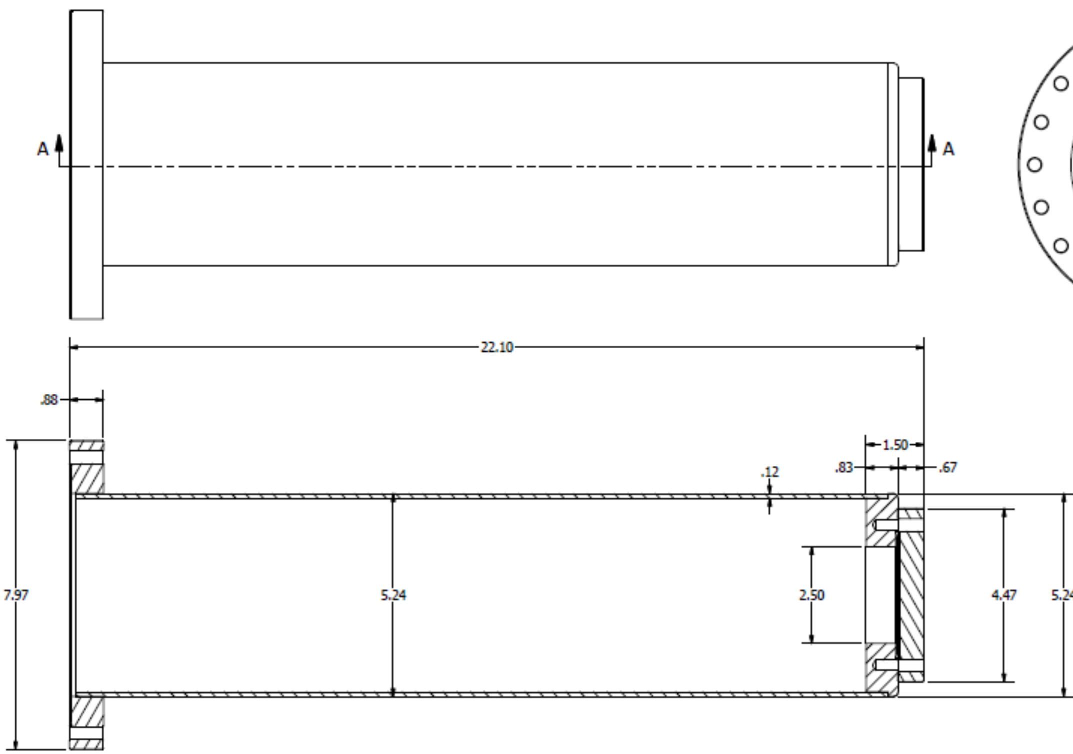
Ø5.240
Ø5.000
Ø4.794
Ø4.331
Ø1.575

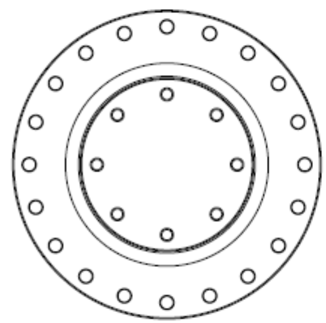


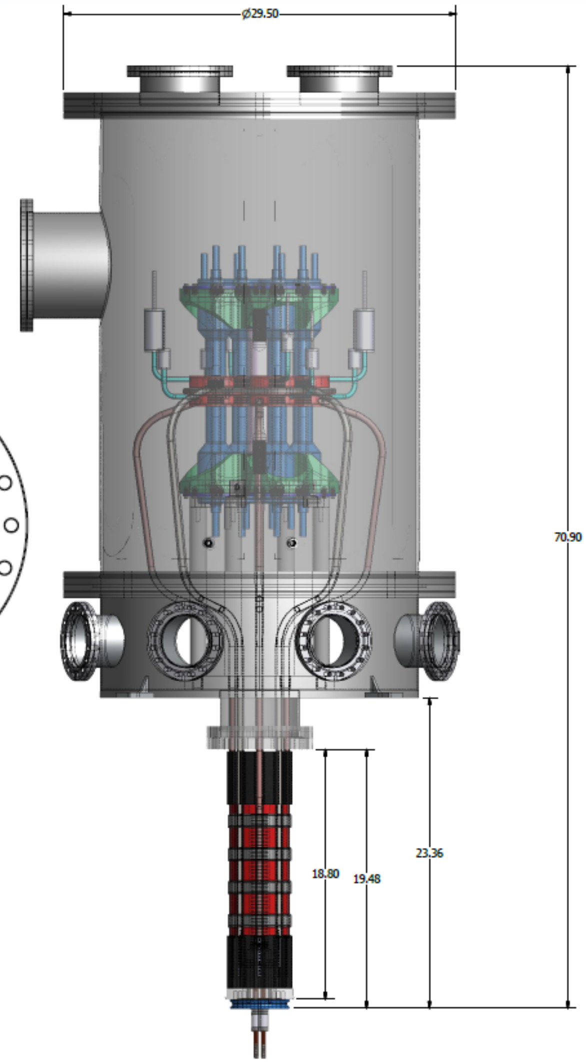
8X 45.00°
∅ 1.57
[∅ 40]
∅ 4.33
[∅ 110]
B
∅ 4.094
[∅ 103.988]
64
SEE VIEW A

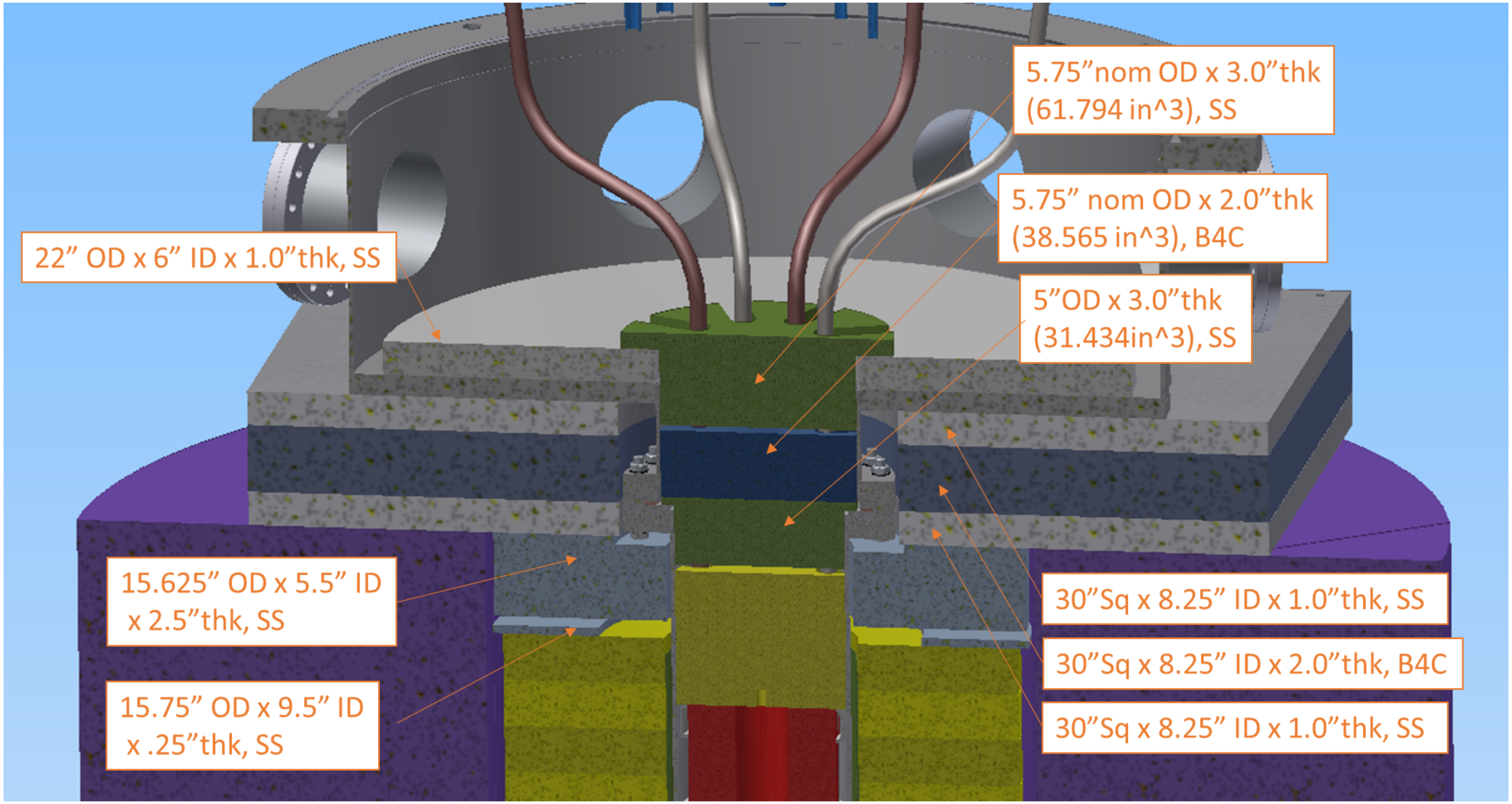


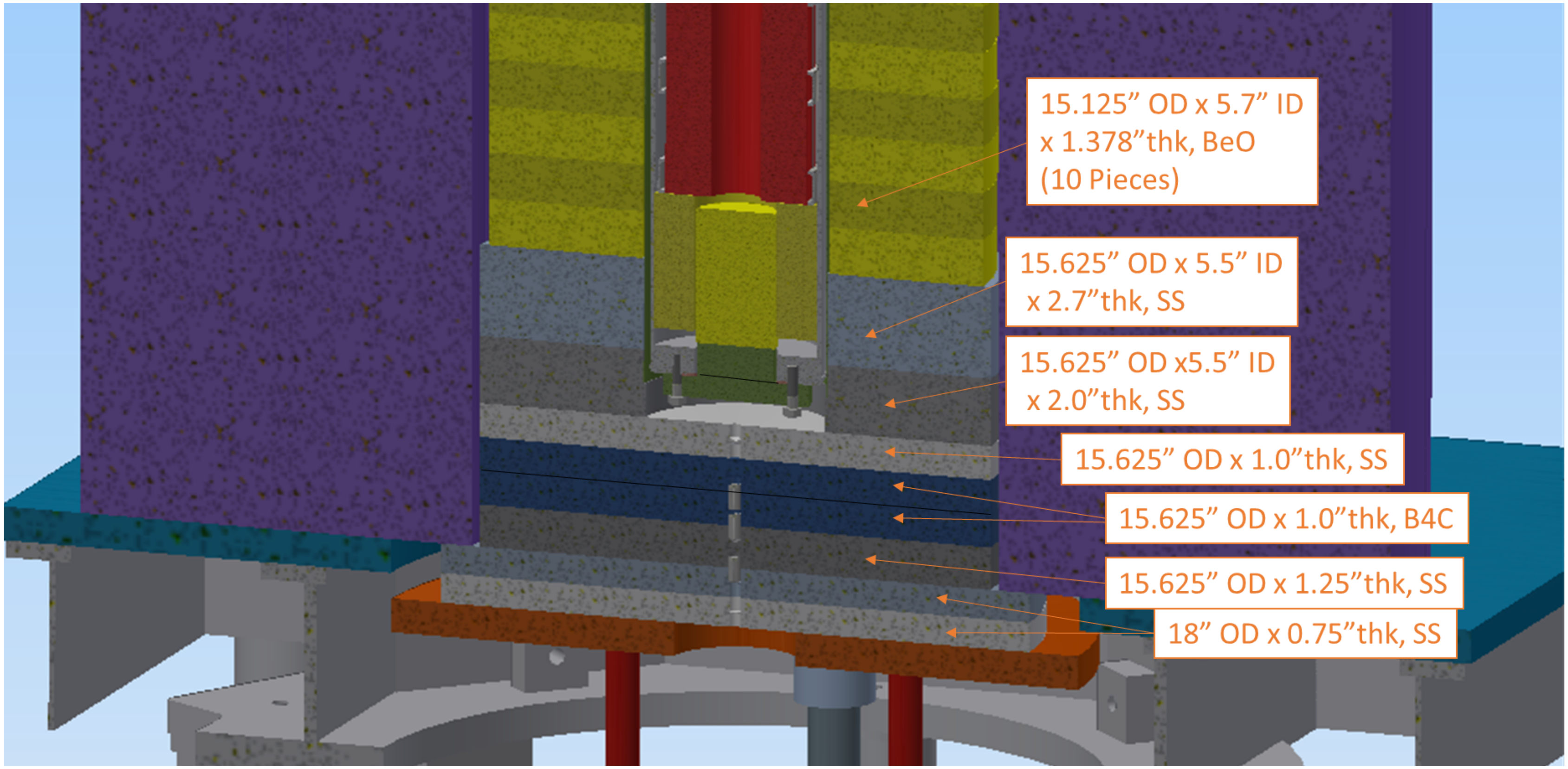
8X INDIVIDUALLY
.002 A B
[0.05]
X Y
∅ .504
[∅ 12.802]
X
Y
64
.504
[∅ 12.802]

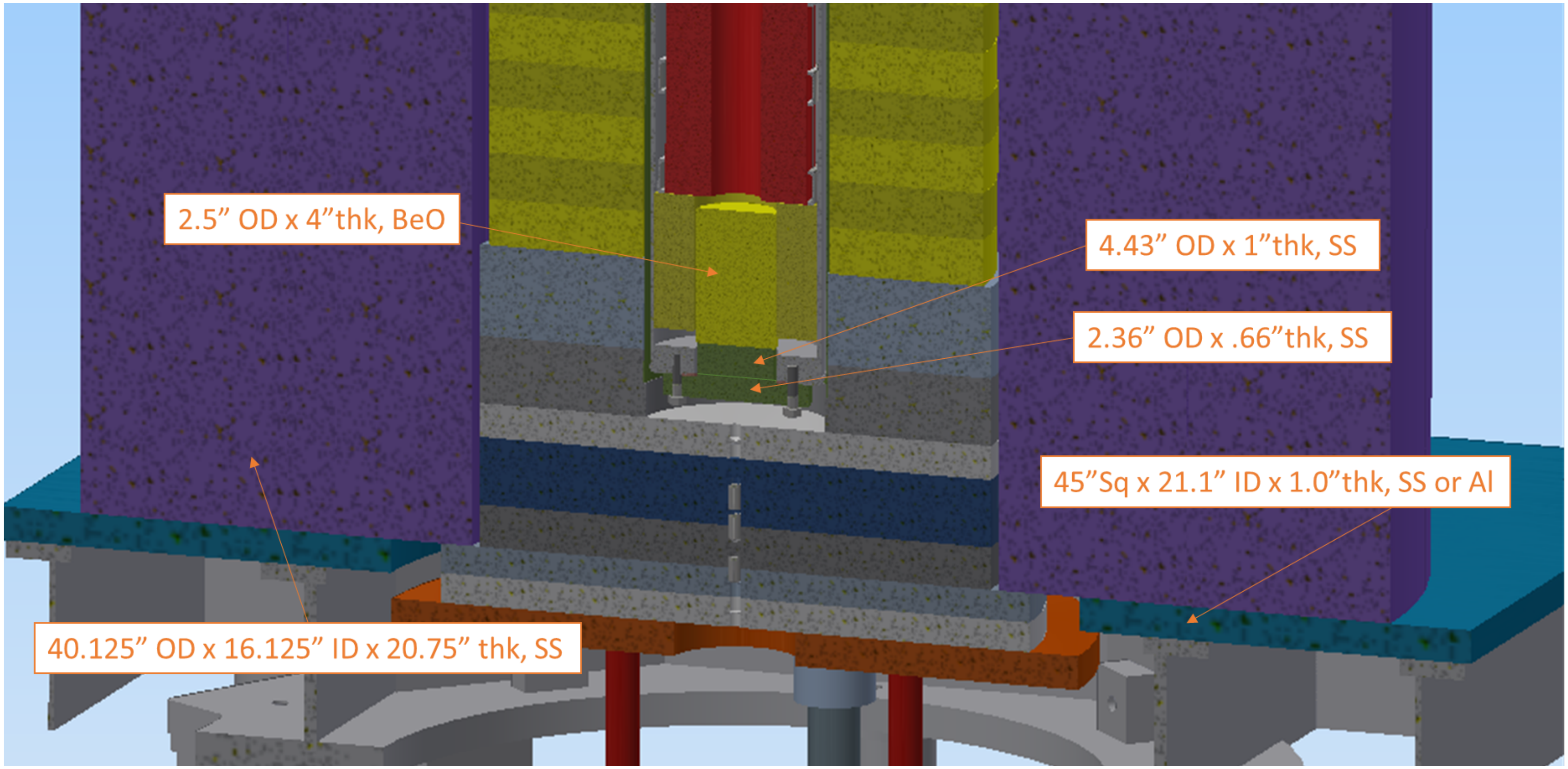

A
A
22.10
.88
1.50
.83
.67
.12
7.97
5.24
2.50
4.47
5.24




ø29.50
70.90
23.36
18.80
19.48


5.75"nom OD x 3.0"thk
(61.794 in^3), SS
5.75" nom OD x 2.0"thk
(38.565 in^3), B4C
22" OD x 6" ID x 1.0"thk, SS
5"OD x 3.0"thk
(31.434in^3), SS
15.625" OD x 5.5" ID
x 2.5"thk, SS
30"Sq x 8.25" ID x 1.0"thk, SS
30"Sq x 8.25" ID x 2.0"thk, B4C
15.75" OD x 9.5" ID
x .25"thk, SS
30"Sq x 8.25" ID x 1.0"thk, SS


15.125” OD x 5.7” ID x 1.378”thk, BeO (10 Pieces)
15.625” OD x 5.5” ID x 2.7”thk, SS
15.625” OD x5.5” ID x 2.0”thk, SS
15.625” OD x 1.0”thk, SS
15.625” OD x 1.0”thk, B4C
15.625” OD x 1.25”thk, SS
18” OD x 0.75”thk, SS


2.5” OD x 4”thk, BeO
4.43” OD x 1”thk, SS
2.36” OD x .66”thk, SS
45”Sq x 21.1” ID x 1.0”thk, SS or Al
40.125” OD x 16.125” ID x 20.75” thk, SS